

The COUPP Dark Matter Search

Results from the first year of deep-underground running at SNOLAB





The COUPP Collaboration

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Fermilab

Steve Brice, Dan Broemmelsiek, Peter Cooper, Mike Crisler, Jeter Hall, Martin Hu, Hugh Lippincott, Erik Ramberg, Andrew Sonnenschein, Fermilab Engineers and Technicians



SNOLAB

Eric Vazquez Jauregui



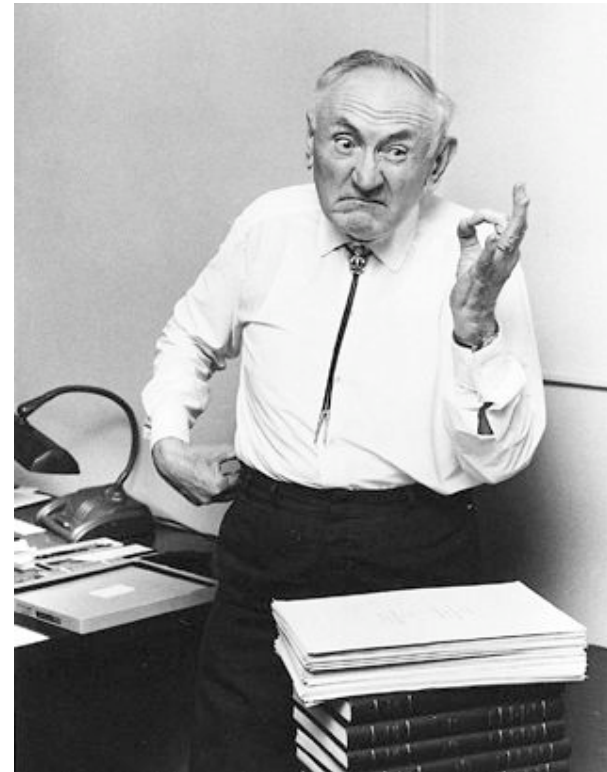


Outline

- The Hunt for Dark Matter
 - Brief History of Dark Matter
 - The WIMP Miracle
 - How to Catch a WIMP
- Bubble Chamber Basics
 - Bubble Chambers as Dark Matter Detectors
- COUPP 4kg @ SNOLAB Results
 - Acoustic Discrimination
 - Limits on WIMP scattering cross sections
 - The road onward...

Early Evidence for Dark Matter

- Fritz Zwicky, 1933
 - Motion of galaxies in Coma Cluster
- Vera Rubin et. al., 1960's
 - Motion of stars, satellites around galaxies



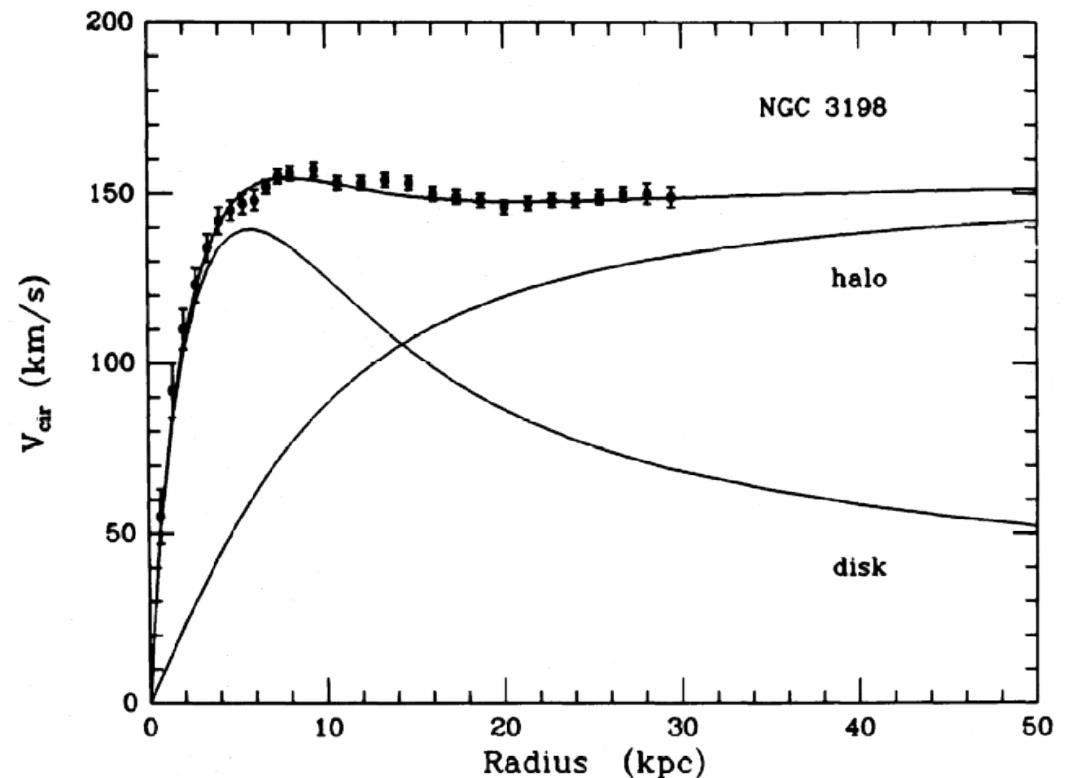
Early Evidence for Dark Matter

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Enter Precision Cosmology: Ω_M

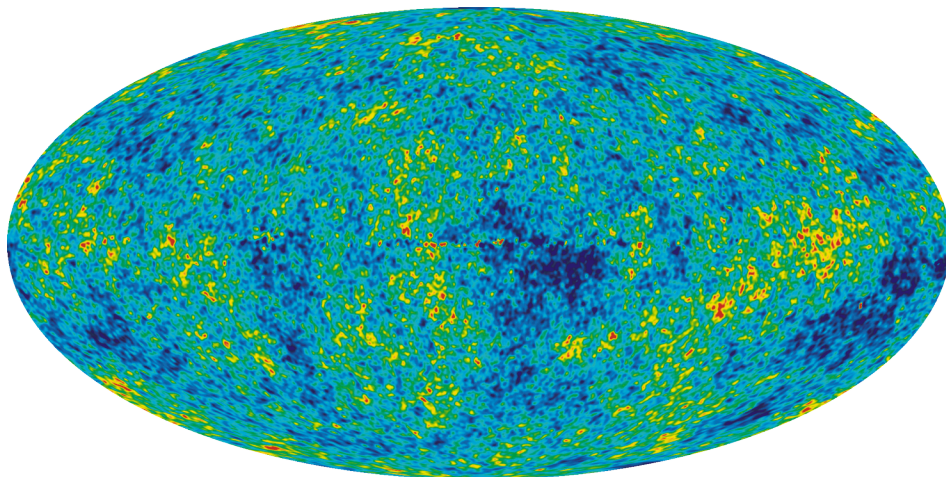
■ Mass in clusters

- Velocity dispersion
- Gravitational lensing

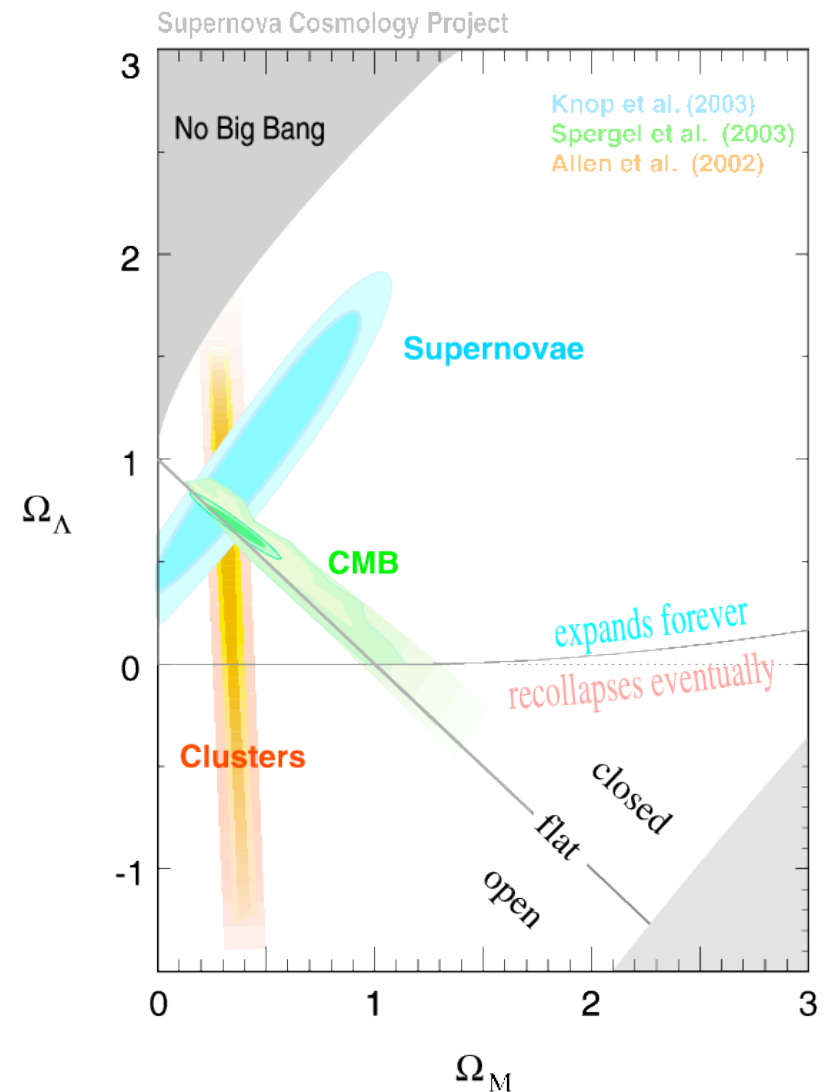
measure Ω_M

■ CMB anisotropy

$$\Omega_\Lambda + \Omega_M = 1$$



Dahl, Fermilab W&C
December 2, 2011



Enter Precision Cosmology: Ω_M

■ Mass in clusters

- Velocity dispersion
- Gravitational lensing

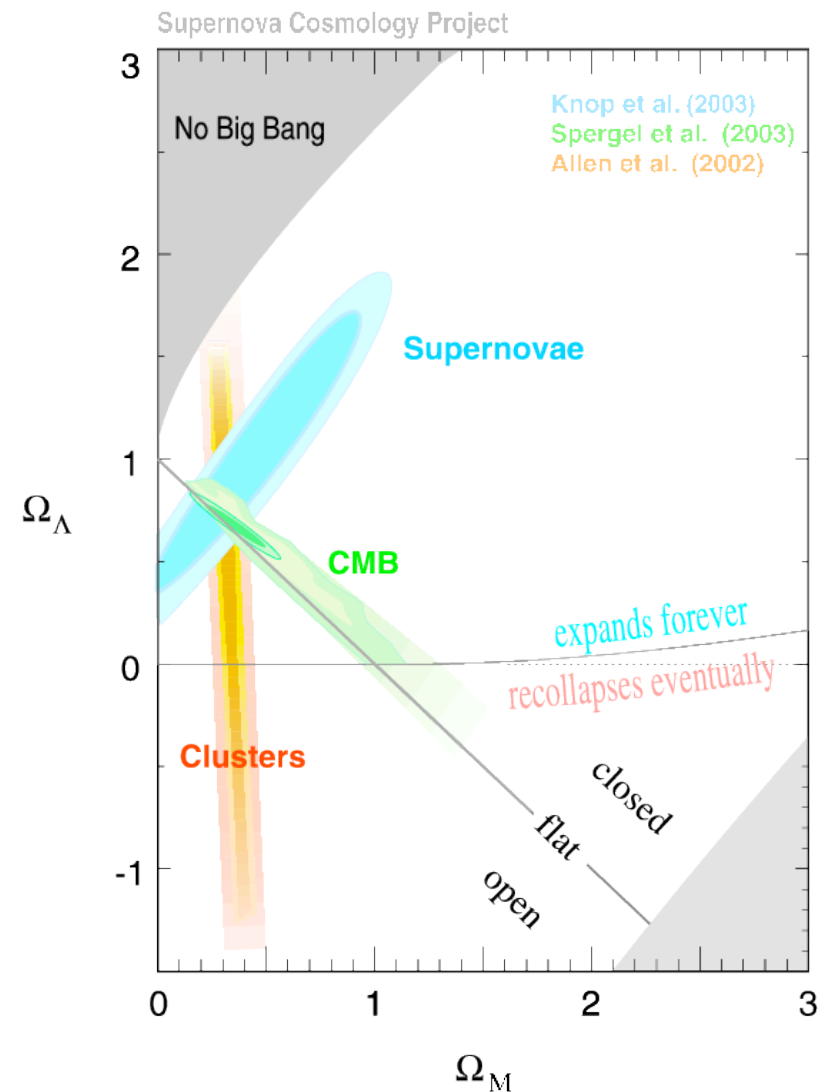
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■ CMB anisotropy

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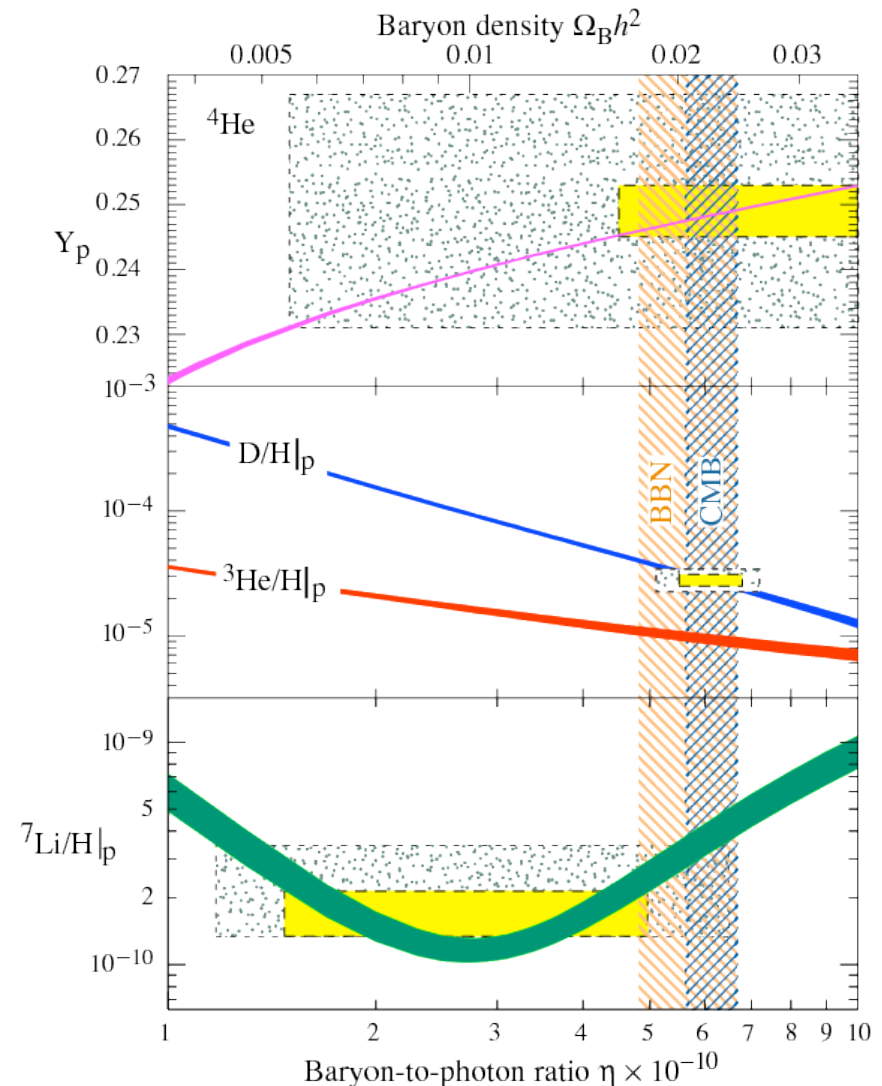
■ Expansion history of Universe

$$\frac{1}{H_0^2} \frac{\ddot{a}}{a} = -\frac{1}{2} \Omega_m \left(\frac{a_0}{a} \right)^3 + \Omega_\Lambda$$



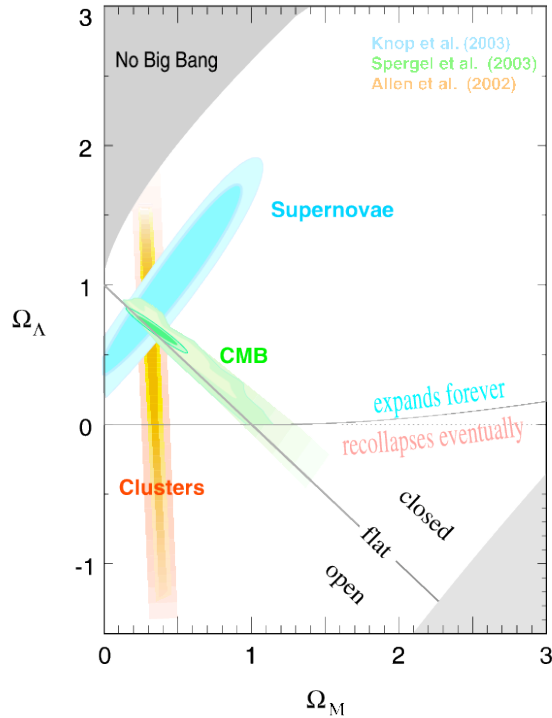
Enter Precision Cosmology: Ω_B

- Big Bang Nucleosynthesis
 - Baryon density determines primordial abundance of light nuclei
- CMB Anisotropy
- X-ray emission from intracluster gas

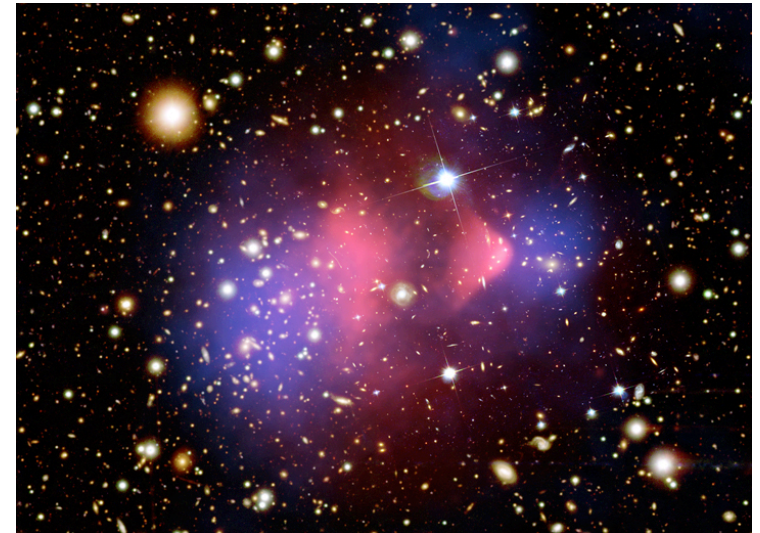
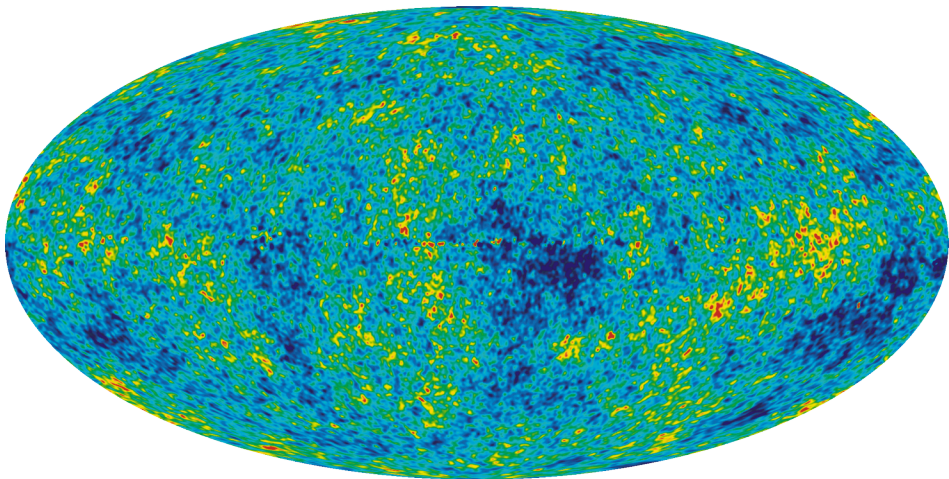
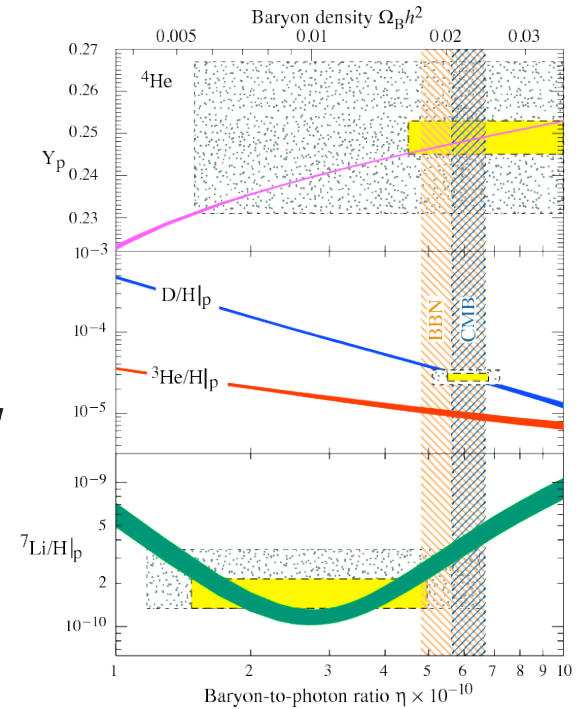
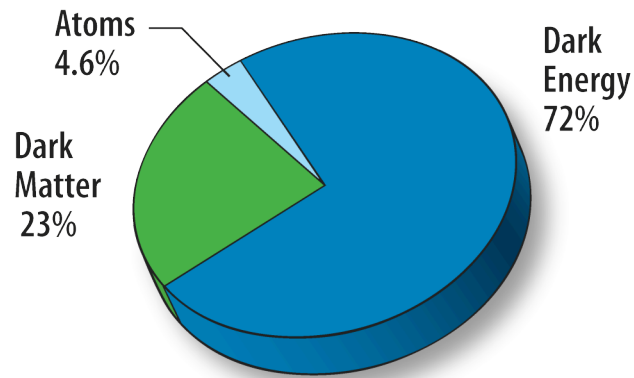




Supernova Cosmology Project



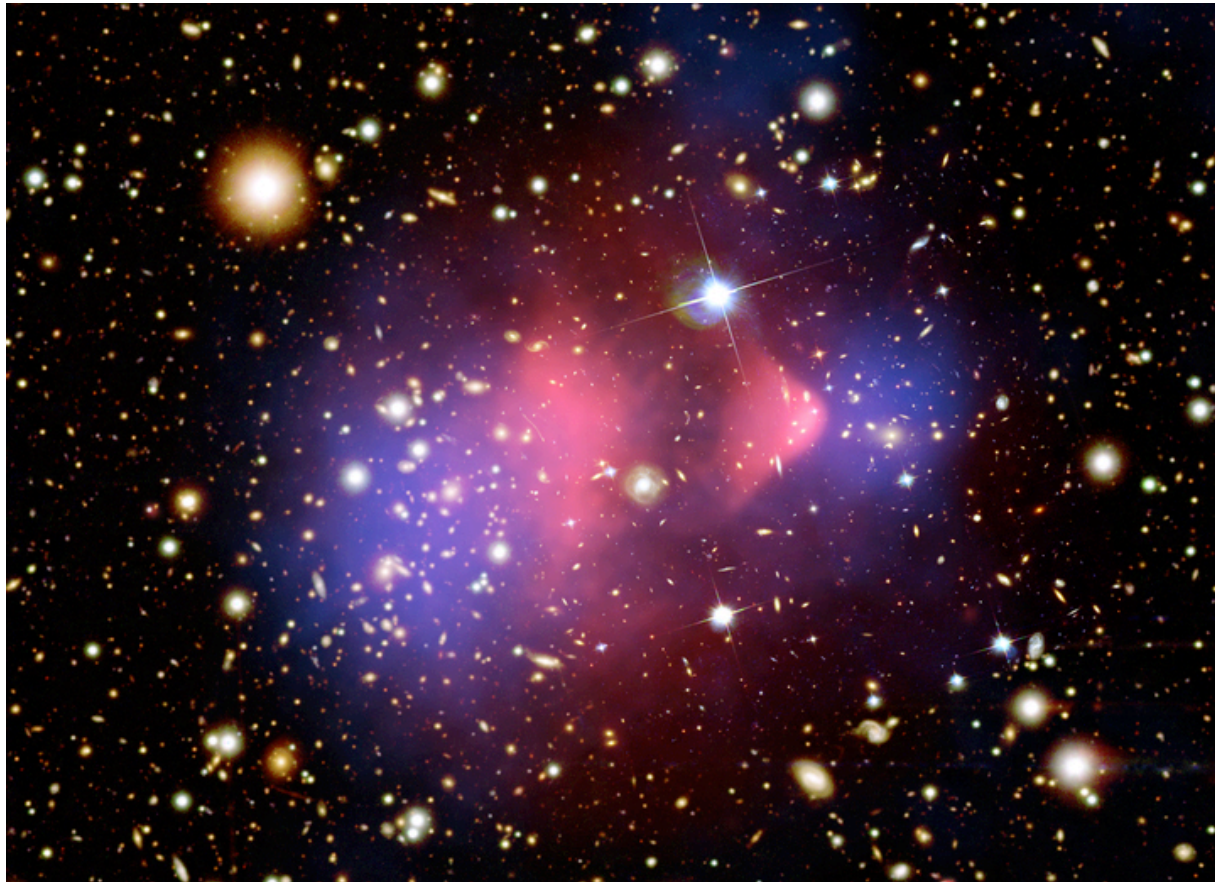
Evidence for Dark Matter



Dahl, Fermilab W&C
December 2, 2011

Two more things...

- Structure Formation requires non-relativistic dark matter
- Bullet Cluster shows non- or weakly-interacting dark matter



Dark Matter ...

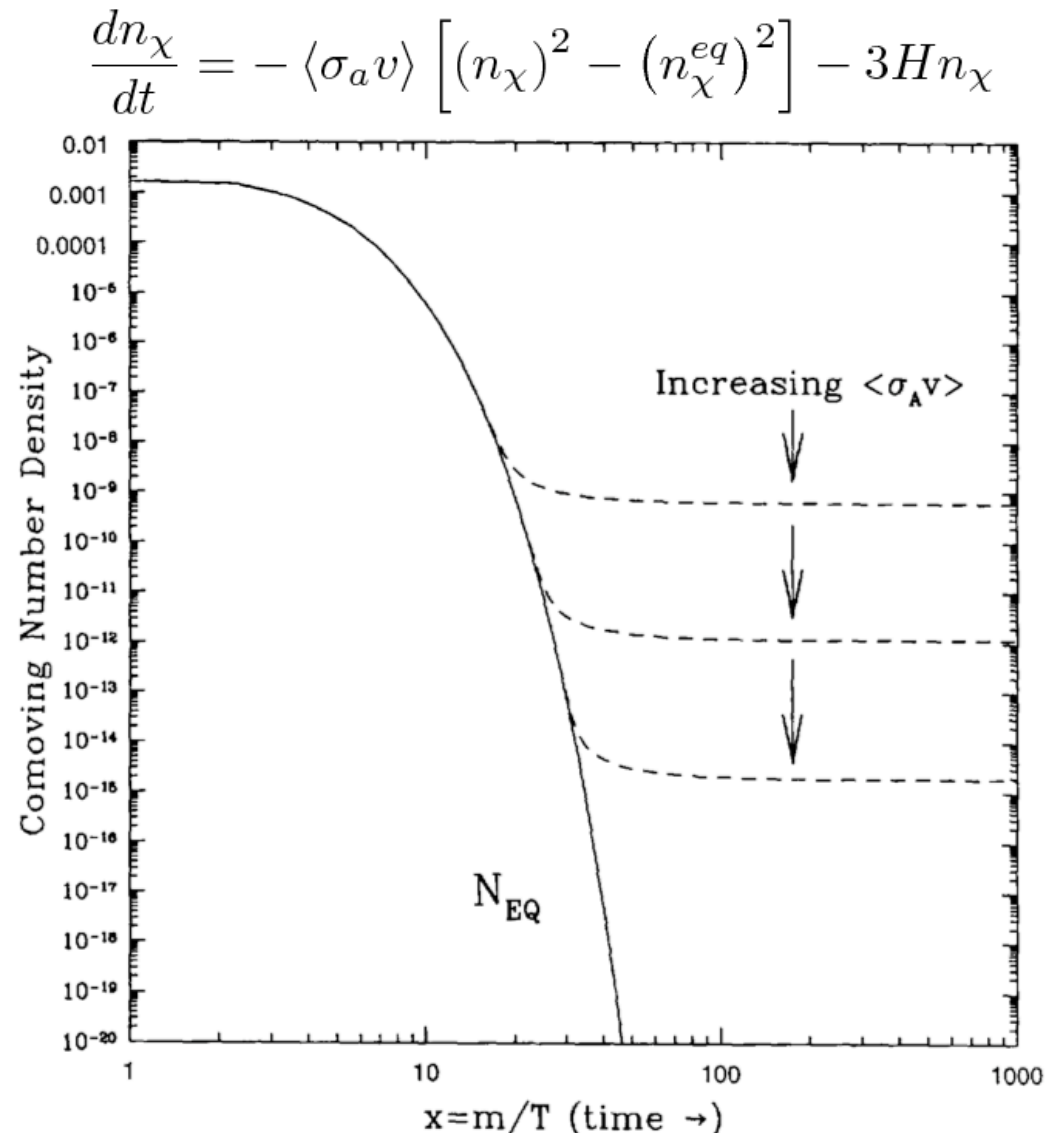
- doesn't emit, absorb, or scatter photons,
- doesn't decay,
- isn't baryonic,
- isn't relativistic,
- doesn't have any strong interactions...



No candidates in the Standard Model!

Relics and Miracles

- Suppose Dark Matter is:
 - Stable Particle (LSP...)
 - Thermal Relic of Big Bang
- Weak-scale interaction gives required density for dark matter



How to Catch a WIMP

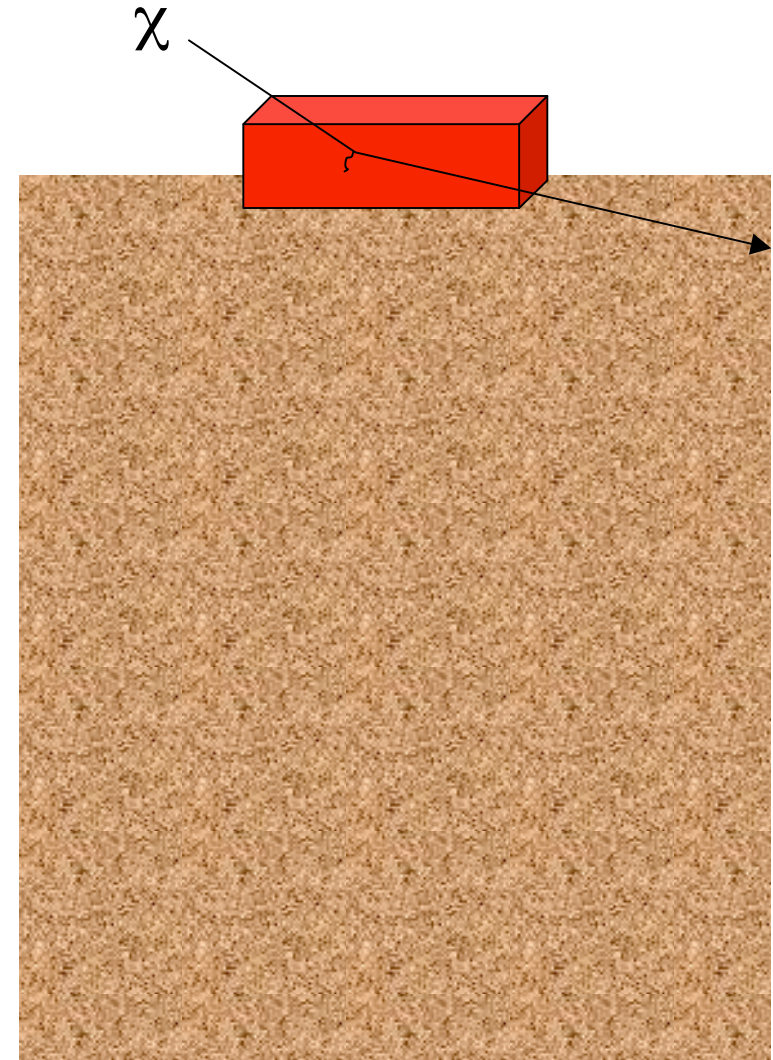
- We live in a Dark Matter halo!

- Local density $\sim 0.4 \text{ GeV/cm}^3$
- rms velocity 230 km/s

- Look for coherent elastic scattering off of nuclei

- Two generic interactions

- Spin-Independent
(e.g., scalar coupling, ...)
Coherent Scattering ($\sigma \propto A^2$)
- Spin-Dependent
(e.g., vector coupling, ...)
Couples to odd-nucleon



How to Catch a WIMP

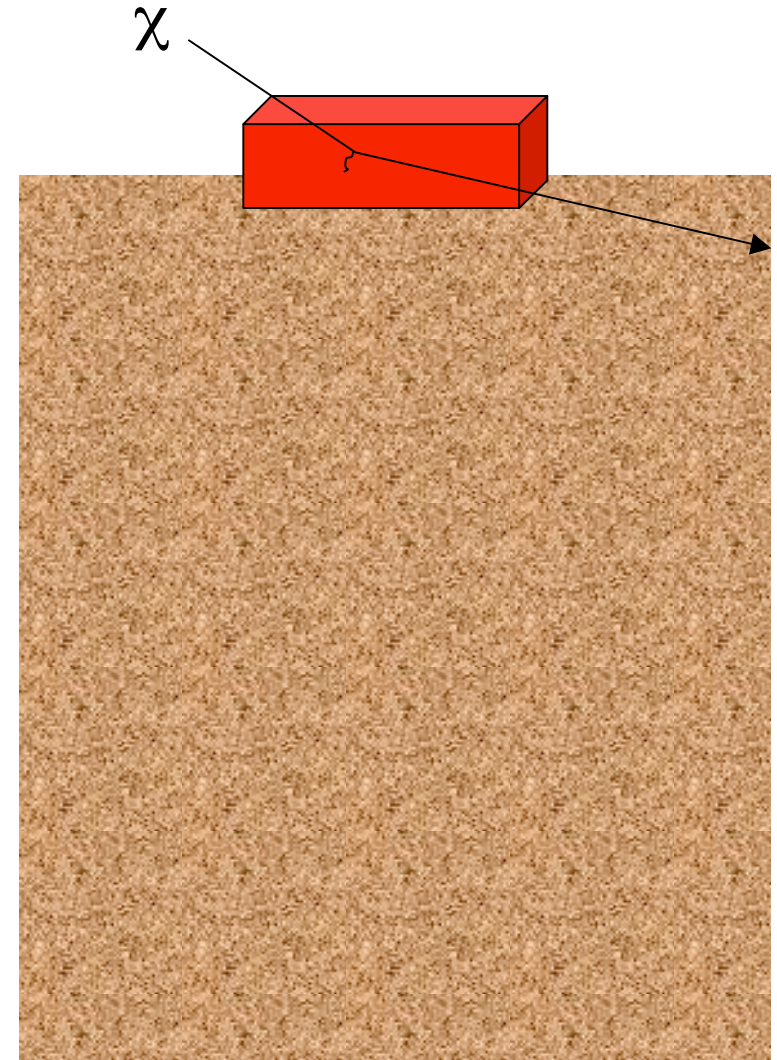
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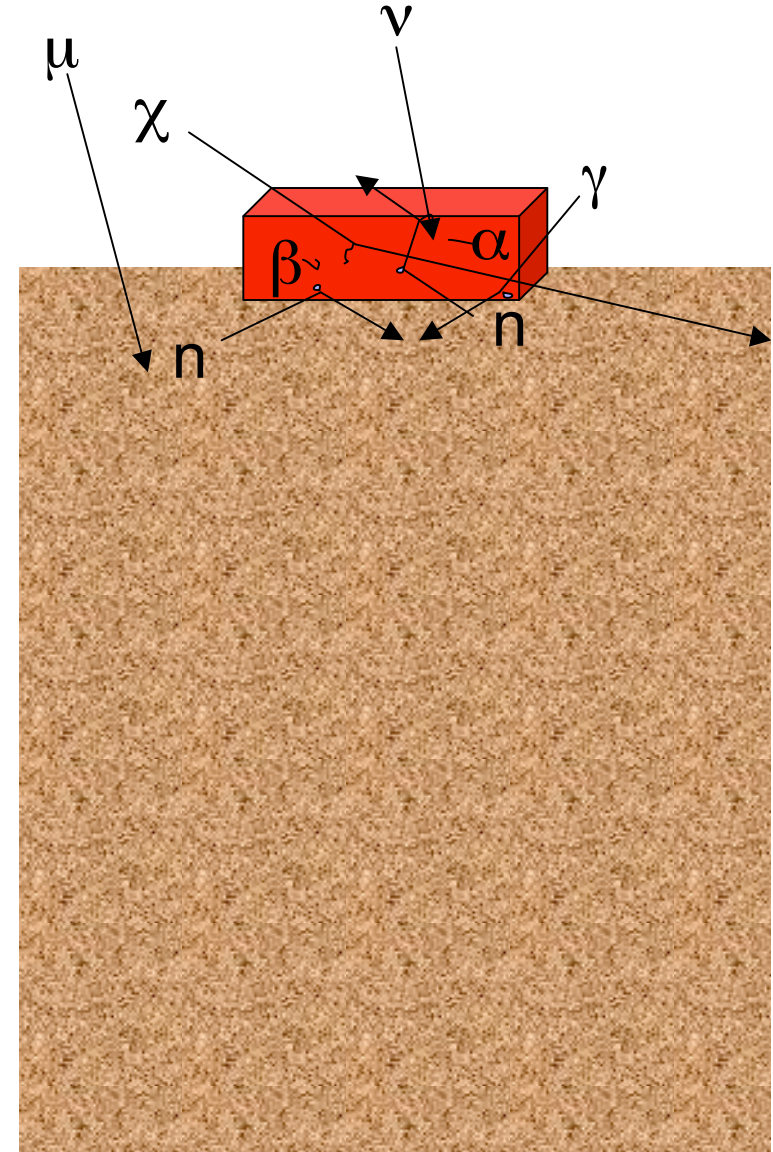
- Recoil energies $O(10) \text{ keV}$
- Rates $\leq O(1) \text{ event / kg-year}$

XENON100, 3 events in 4 kg-years,
(consistent with expected background)
Phys. Rev. Lett. **107**, 131302 (2011)



How to Catch a WIMP

- We live in a Dark Matter halo!
 - Local density $\sim 0.4 \text{ GeV/cm}^3$
 - rms velocity 230 km/s
- Look for coherent elastic scattering off of nuclei
 - Recoil energies $O(10) \text{ keV}$
 - Rates $\leq O(1) \text{ event / kg-year}$
 - Many backgrounds from natural radioactivity



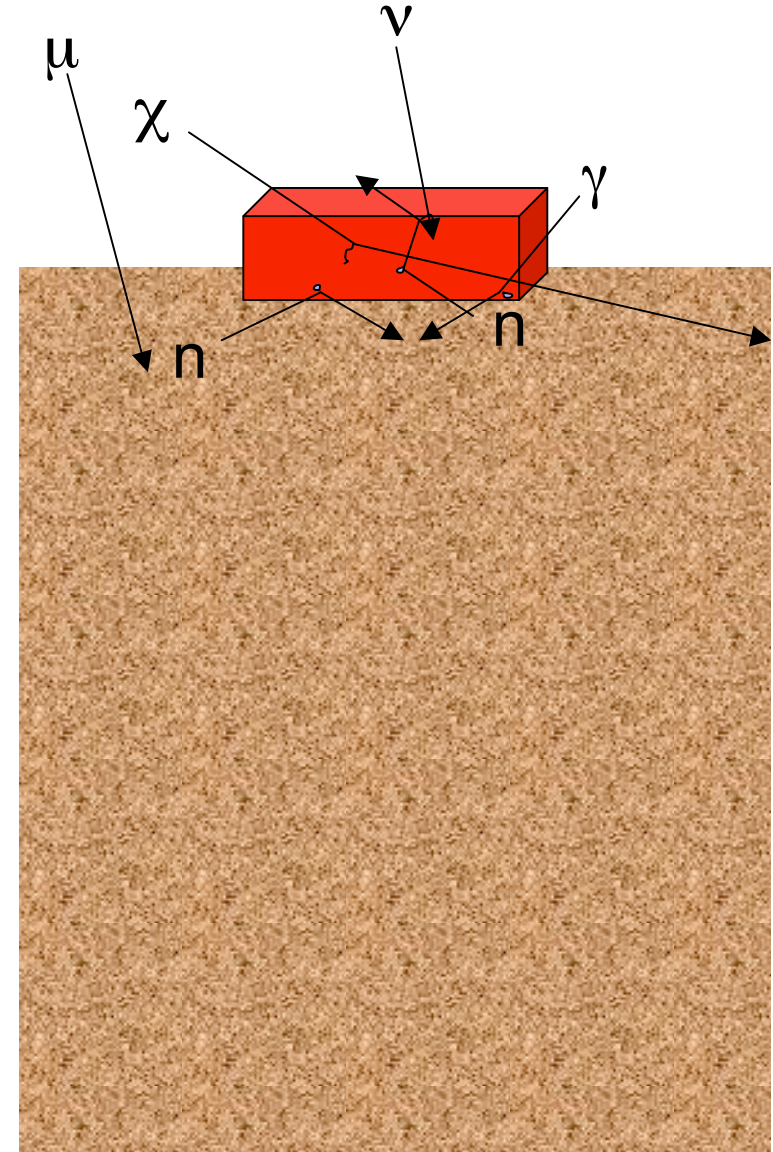
Internal Backgrounds

■ β -decays

- Screen and purify detector materials
- **Discriminate** between electron tracks and nuclear recoils

■ α -decays

- Screen and purify detector materials
- **Discriminate** between $O(10)$ keV WIMP events and 5 MeV α -decays



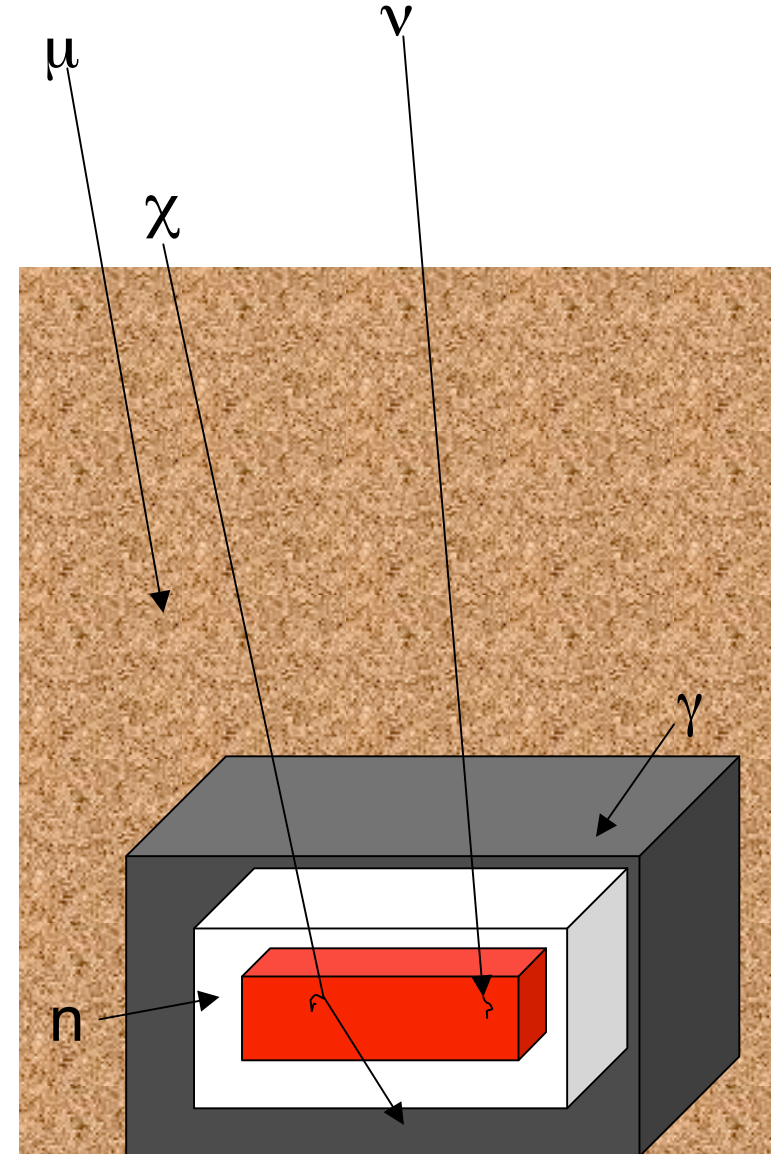
External Backgrounds

■ neutrons

- Produced by fission, (α, n) reactions, cosmic rays
- Give elastic scatters off nuclei, same as WIMP signal
- Shield detector with low-z moderator, screen materials, go underground
- Reject multiple-scatters

■ gammas

- Compton Scatter in detector
- **Discriminate** between electron tracks and nuclear recoils
- Shield detector with high-z materials, screen components
- Reject multiple-scatters

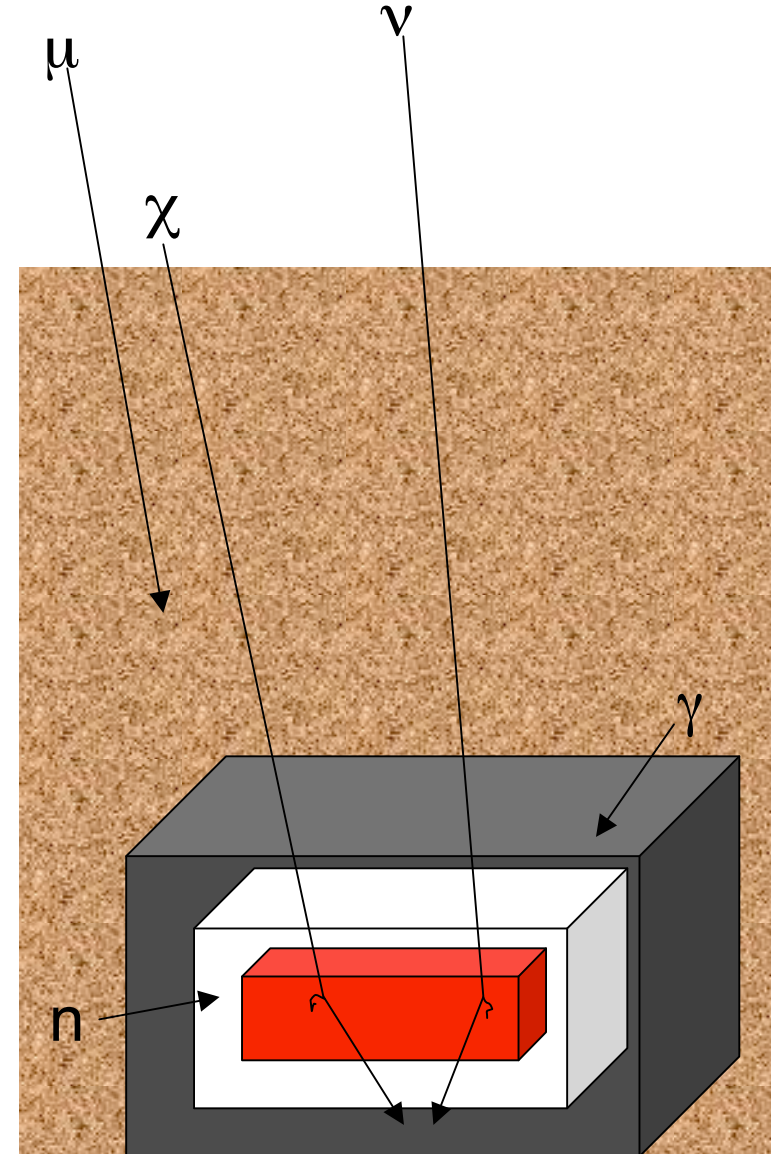


External Backgrounds

■ neutrinos

- **Discriminate** against charged-current interactions
- No defense against high-energy neutrino neutral-current elastic scatters off nuclei

Irreducible neutrino background
at $O(1)$ event / 10 ton-years





Detector Requirements

- Sensitivity to $O(10)$ keV nuclear recoils
- Scalability to ton-scale targets
- Discrimination against backgrounds

Detector Styles

■ Cryogenic

- CDMS, EDELWEISS
- CRESST

\$ \$ \$

Ge, phonon + charge

CaWO₄, phonon + scintillation

■ Liquid Noble

- XENON, LUX, ZEPLIN
- XMASS
- WARP, ArDM, Darkside
- DEAP/CLEAN

\$ \$

Xe, TPC (charge + scintillation)

Xe, scintillation only

Ar, TPC (charge + scintillation)

Ar, scintillation only

■ Superheated Fluid

- COUPP
- PICASSO, SIMPLE

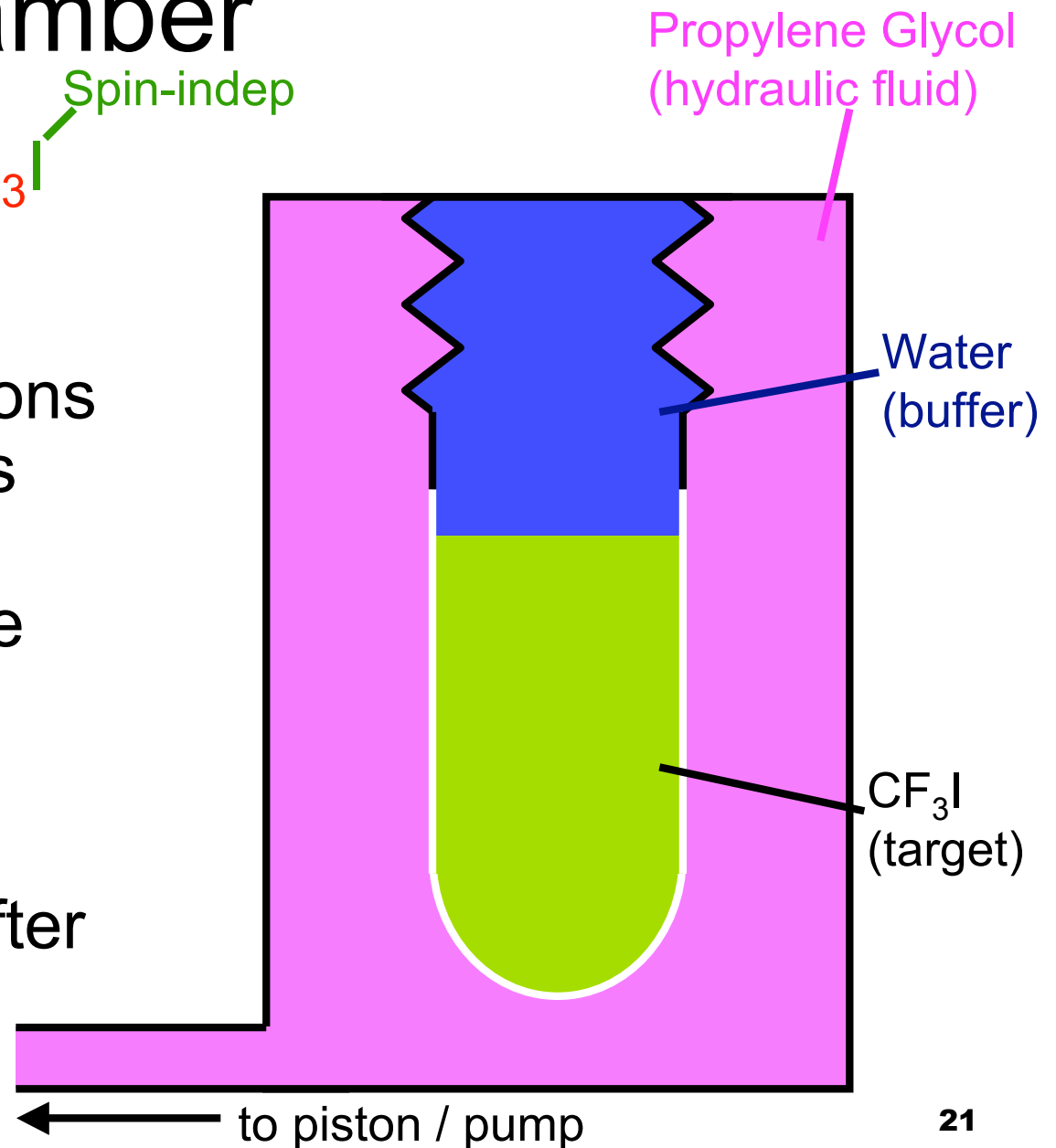
\$

CF₃I, bubble chamber

C₄F₁₀, superheated droplets

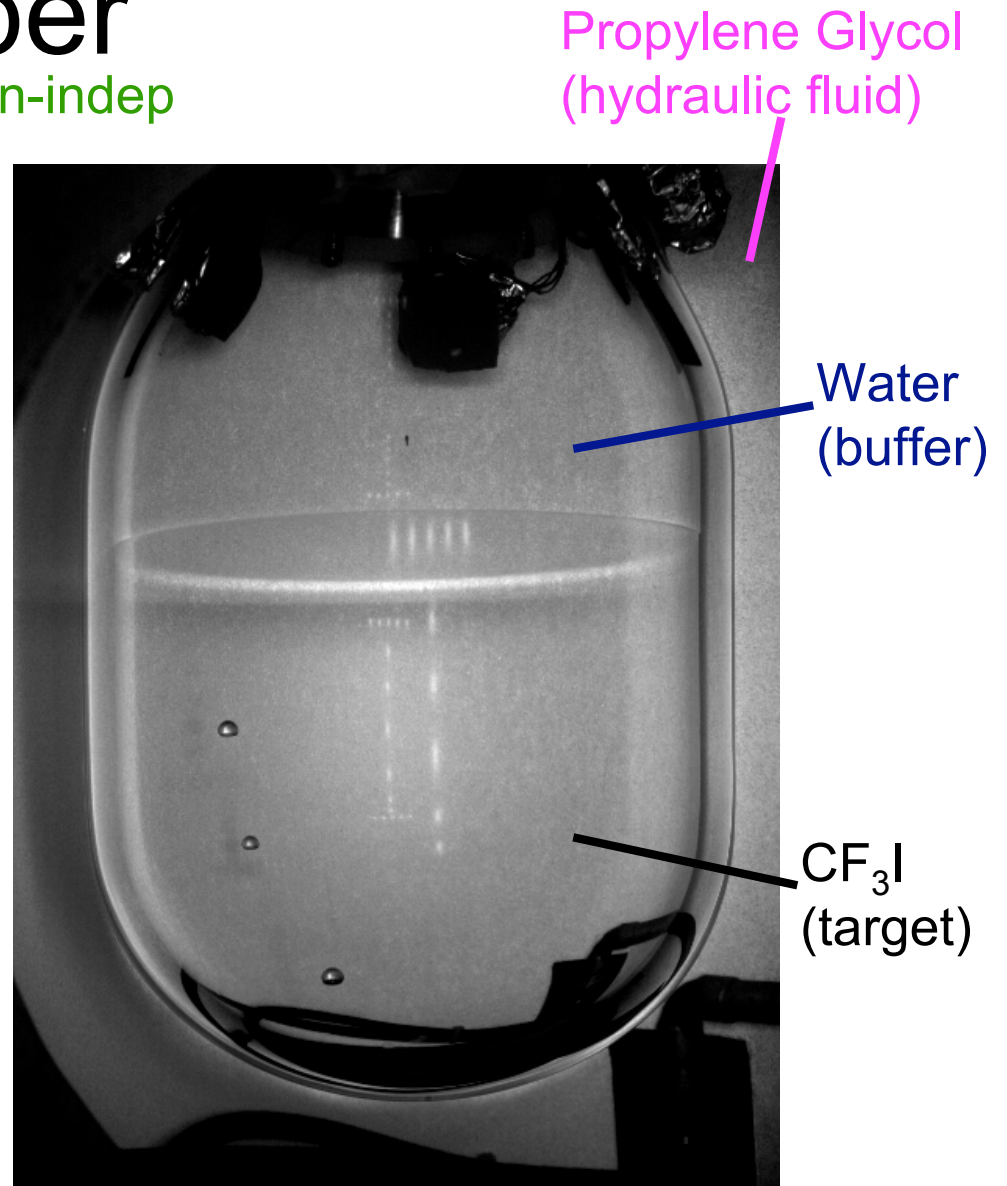
Bubble Chamber

- Superheated CF_3I target Spin-indep
Spin-dep
- Particle interactions nucleate bubbles
- Cameras capture bubbles
- Chamber recompresses after each event



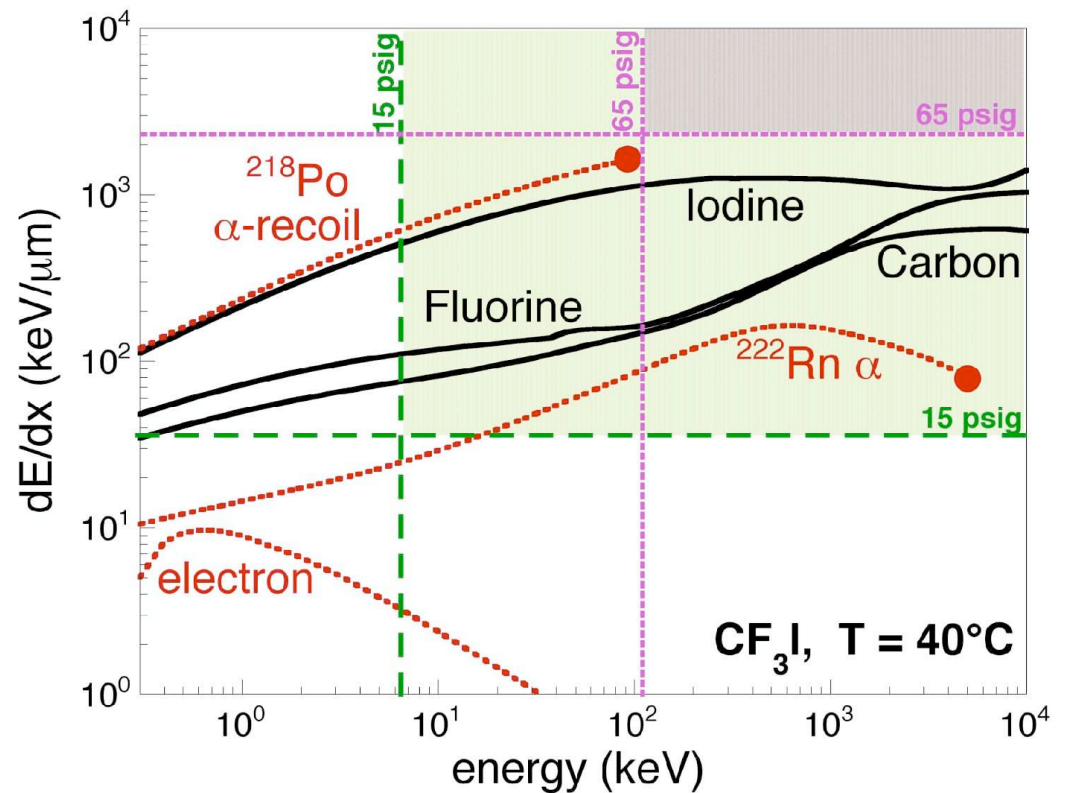
Bubble Chamber

- Superheated CF_3I target Spin-dep Spin-indep
- Particle interactions nucleate bubbles
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Review

- Only proto-bubbles with $r > r_{\text{crit}}$ grow to be macroscopic
- Critical proto-bubble requires minimum dE within minimum volume
- Recoil must be over thresholds in both E and dE/dx



No sensitivity to γ 's or β 's,
but α 's do make bubbles

3 basic event types

■ alpha-decays

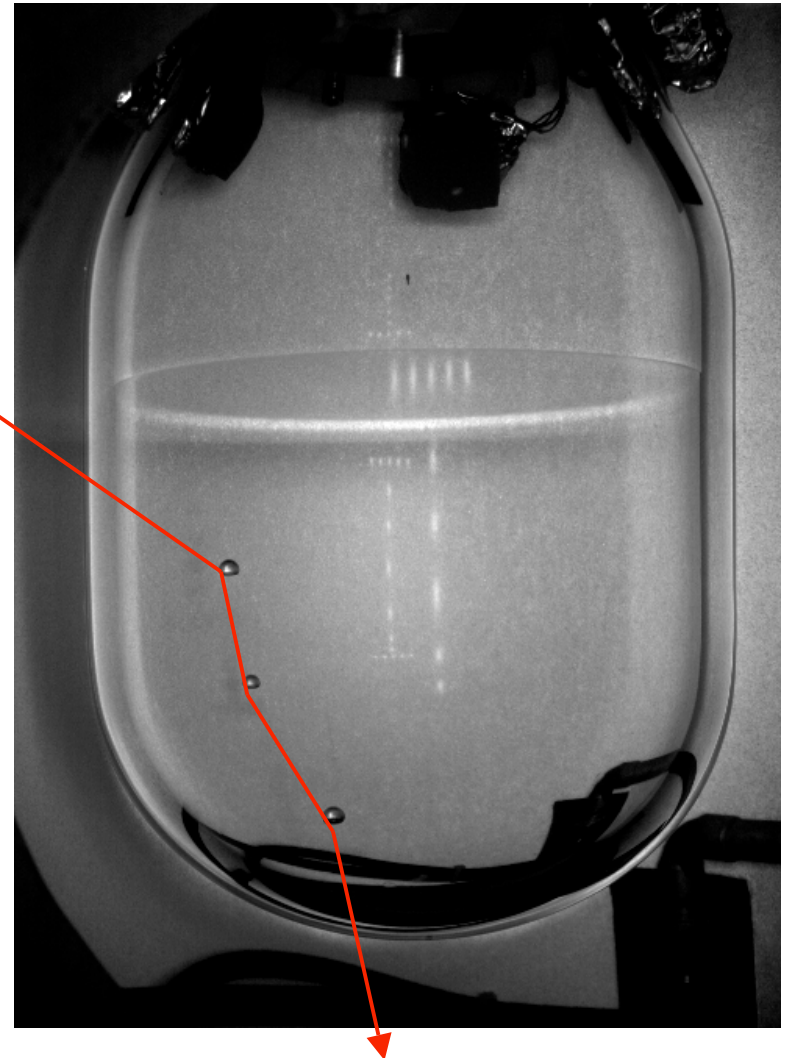
- Nuclear recoil + 40 μm alpha track
- 1 bubble

■ neutrons

- Nuclear recoils, mean free path ~ 20 cm
- 3:1 single-multiple ratio in COUPP 4kg

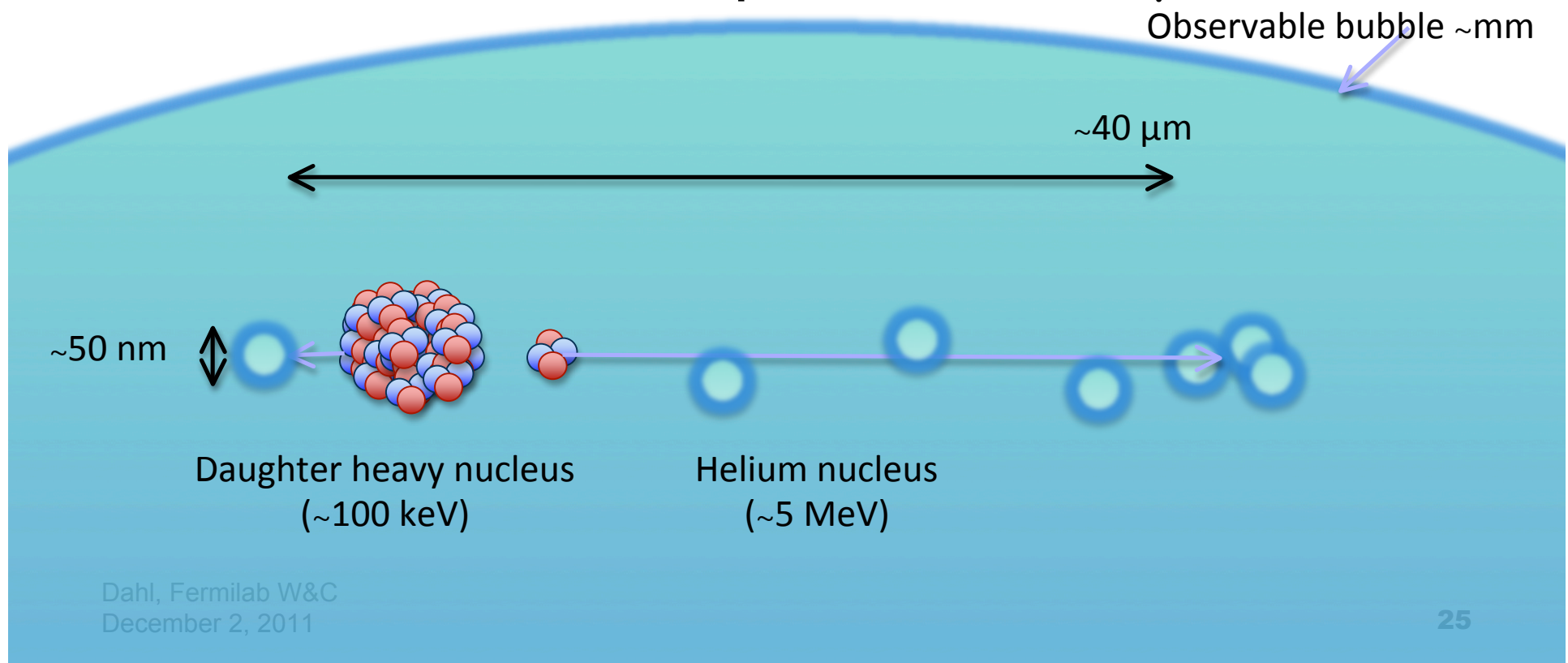
■ WIMPs

- Nuclear recoil, mean free path $> 10^{12}$ cm
- 1 bubble



Acoustic Discrimination

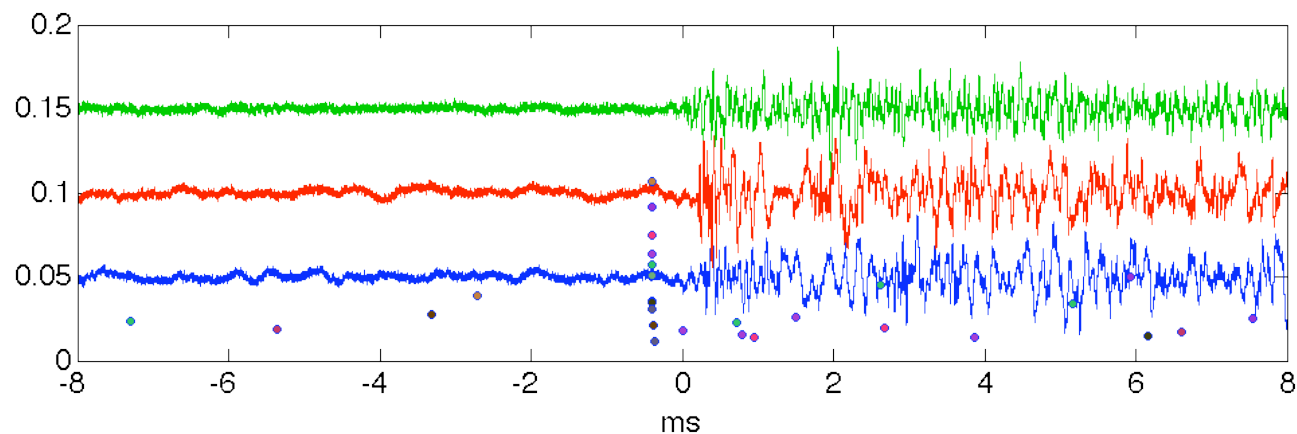
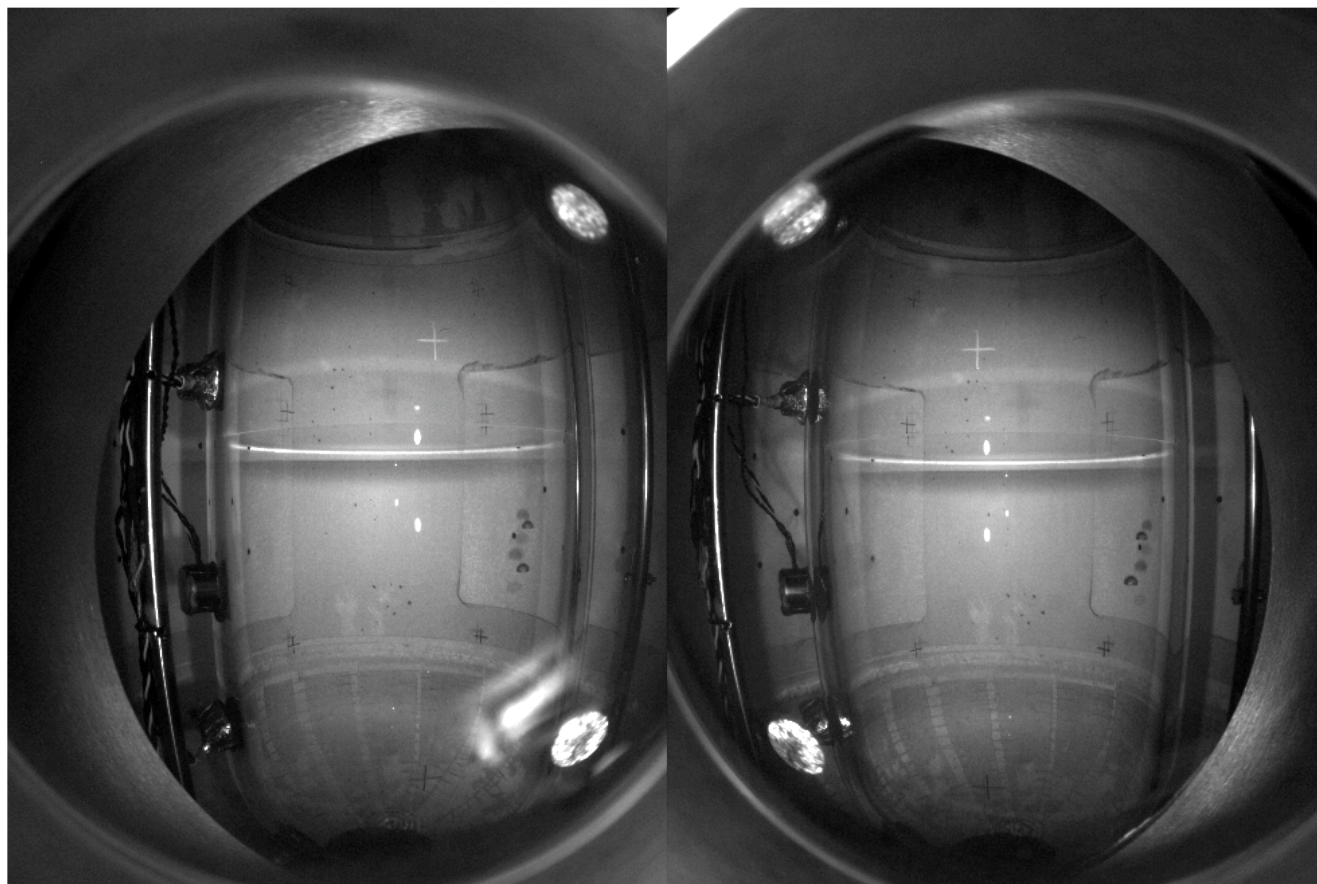
- Alpha louder when probing length scales $< 40\ \mu\text{m}$
- Acoustic emission peaks at $\sim 10\ \mu\text{m}$



COUPP 60 @ MINOS

SNOLAB
installation
in 2012...

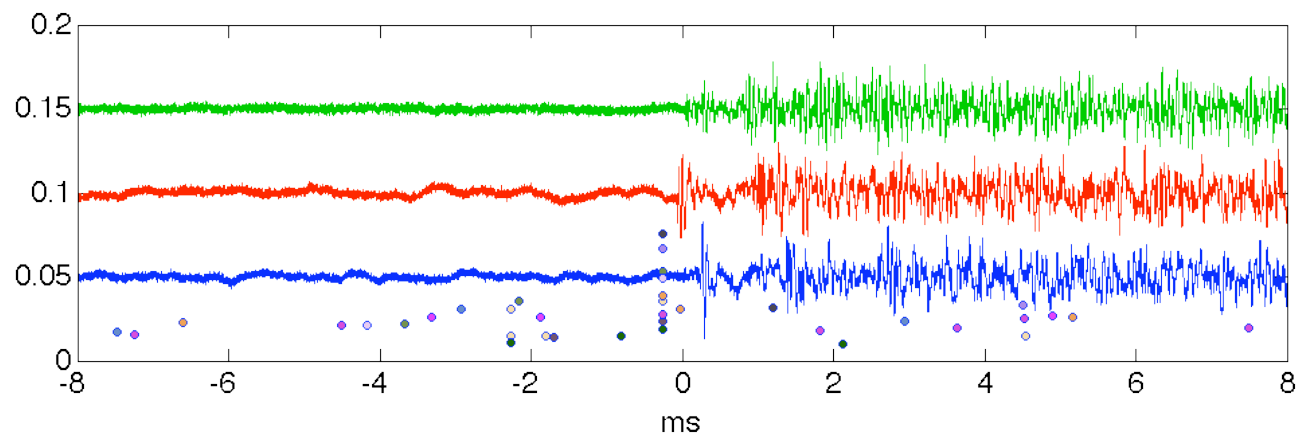
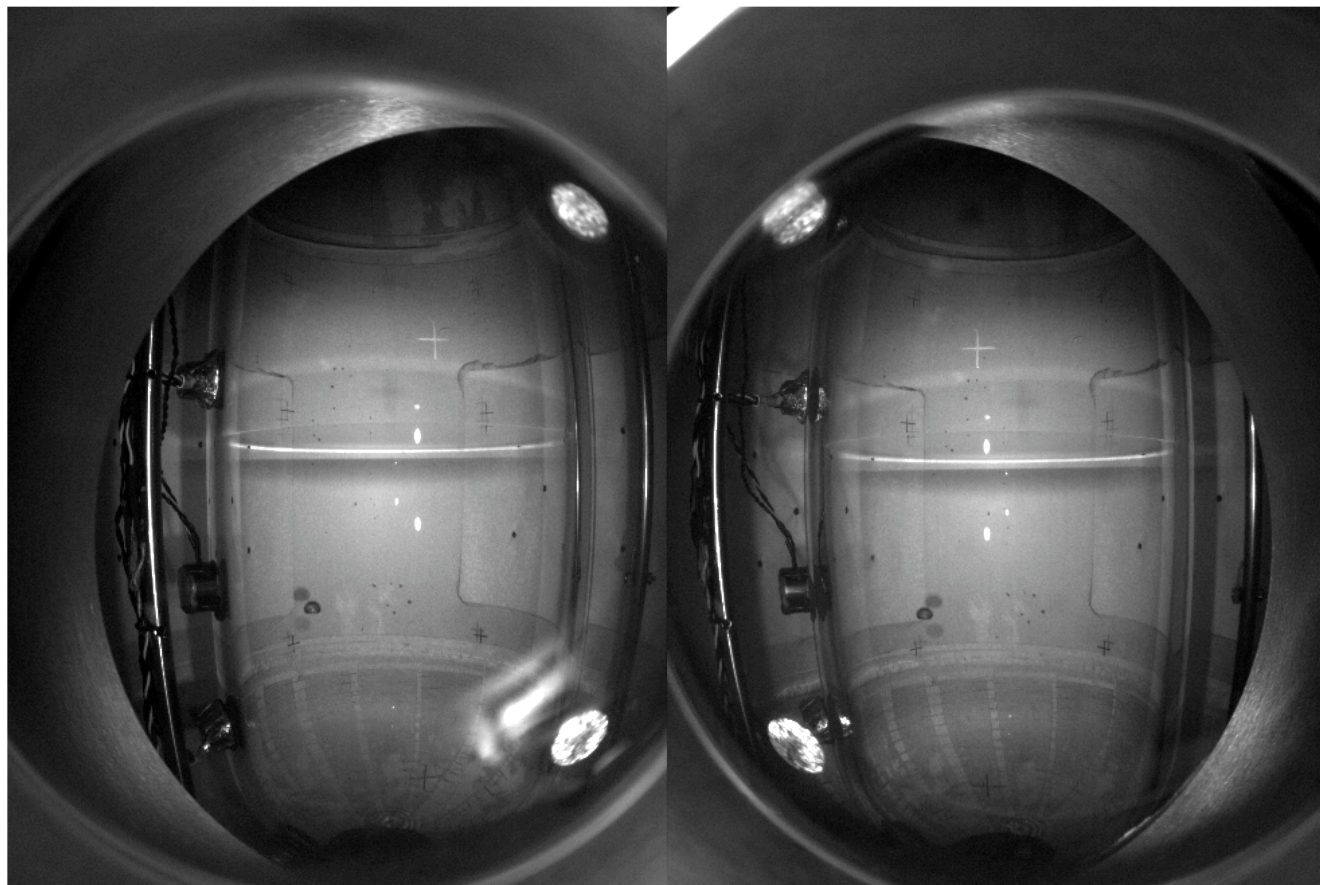
- Cosmic-induced neutron (2 bubbles)



COUPP 60 @ MINOS

SNOLAB
installation
in 2012...

- Cosmic-induced neutron (1 bubble)

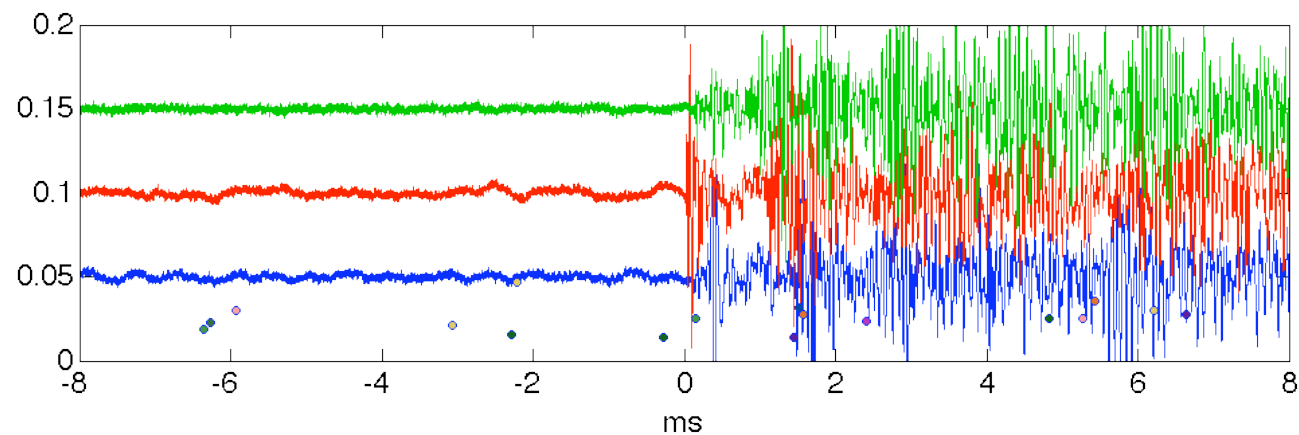
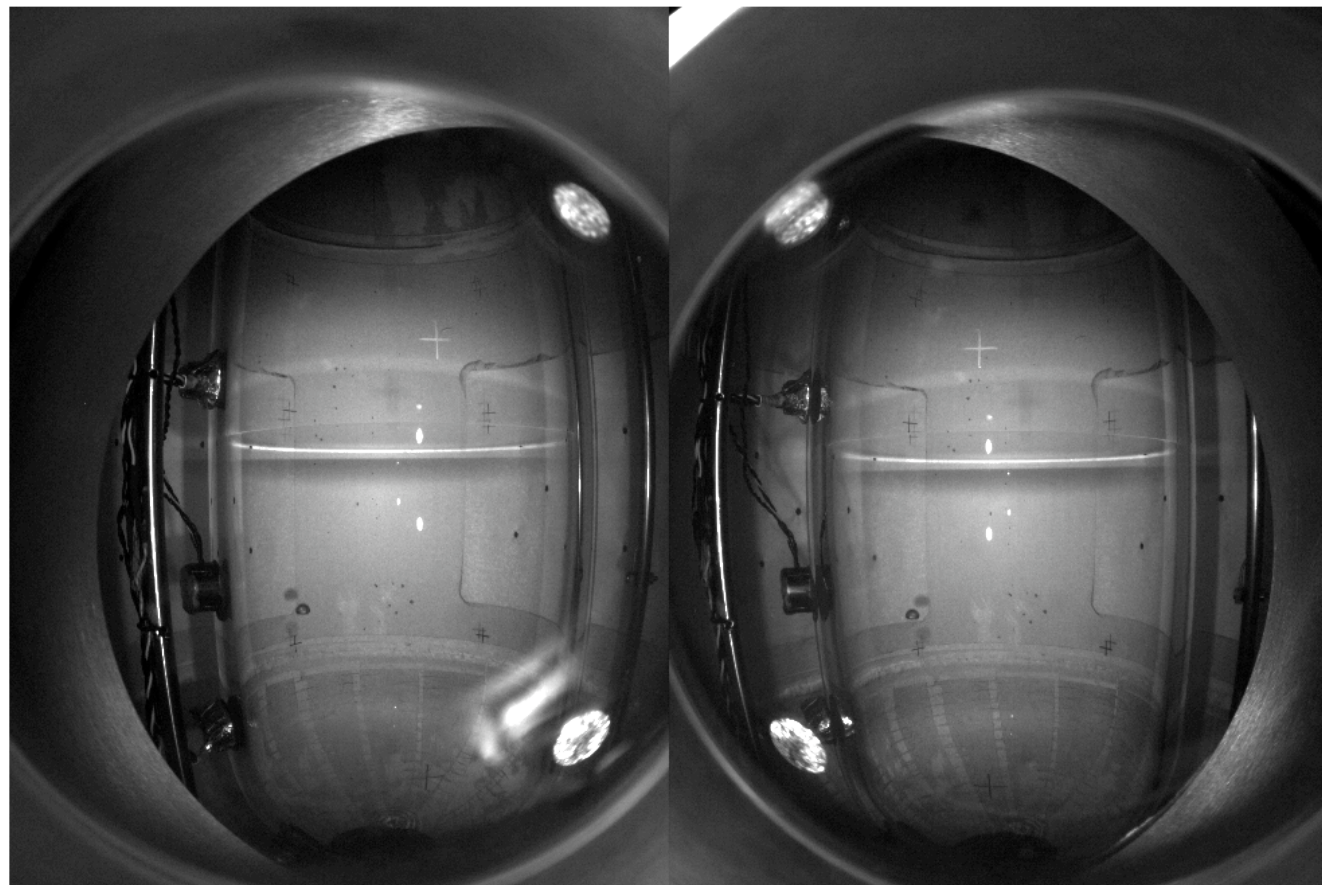


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December 2, 2011

COUPP 60 @ MINOS

SNOLAB
installation
in 2012...

- Alpha-decay
(1 bubble)



Sudbury, Ontario



6800 Feet Down



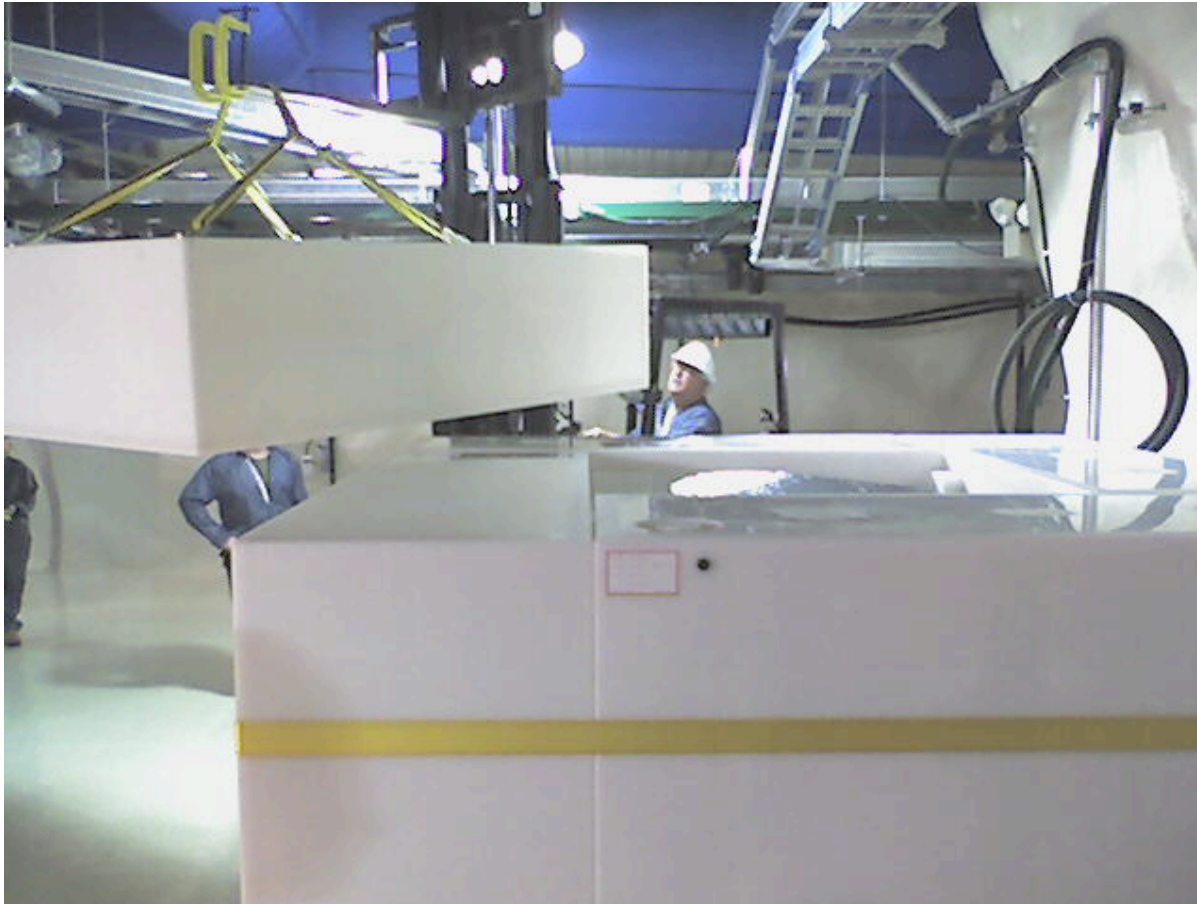
COUPP 4kg @ SNOLAB



Installation Begins:
July 27, 2010

July 27, 2010, DAQ and Pressure Control
Move Underground

COUPP 4kg @ SNOLAB



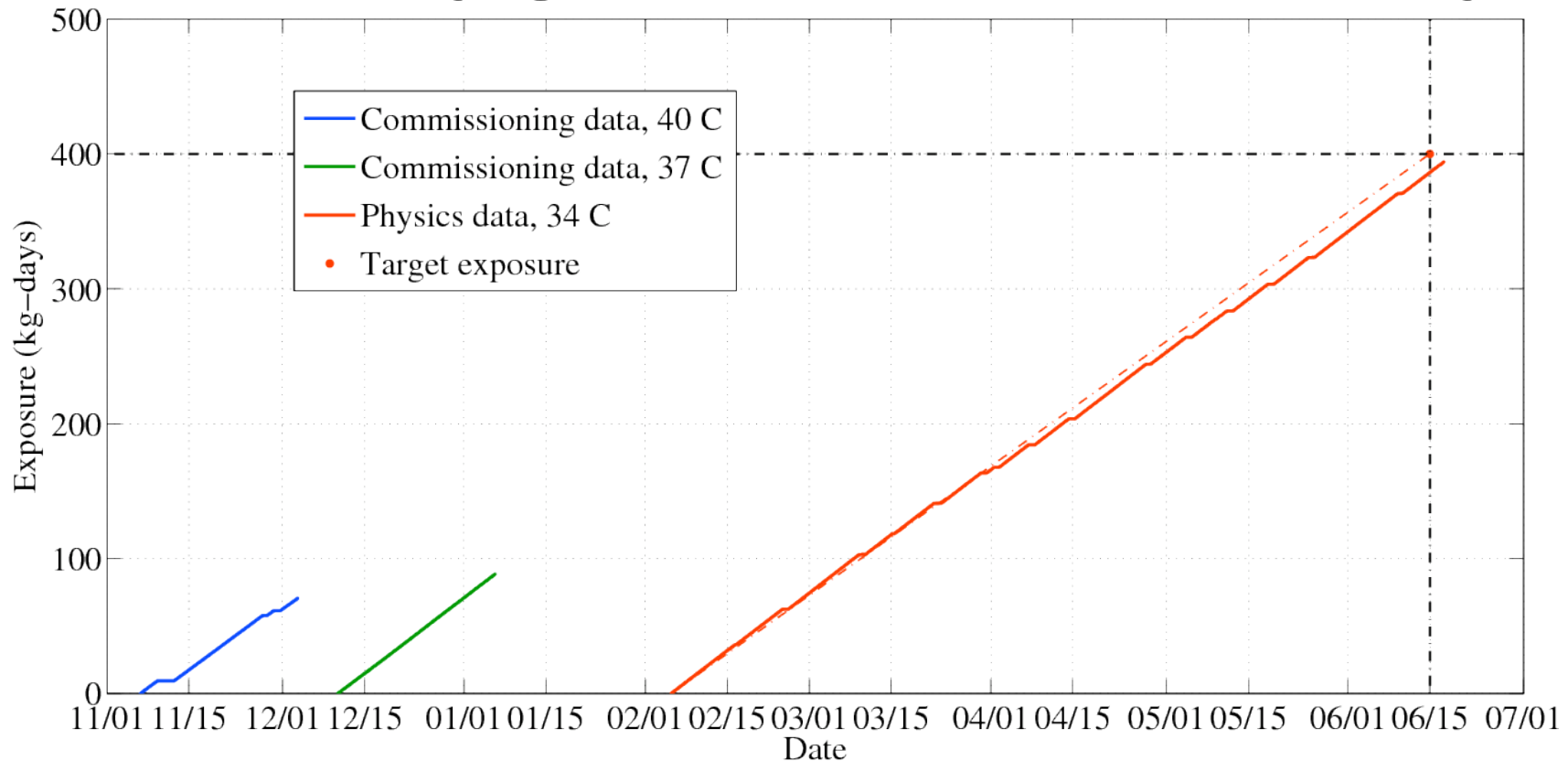
Nov 3, 2010, Shield is completed
Physics data begins!

Dahl, Fermilab W&C
December 2, 2011

One leaky accumulator,
a few leaky plumbing lines,
a slightly overstretched bellows, and
one unusual occurrence report later...

Installation Ends:
Nov 3, 2010

COUPP 4kg @ SNOLAB, WIMP search log

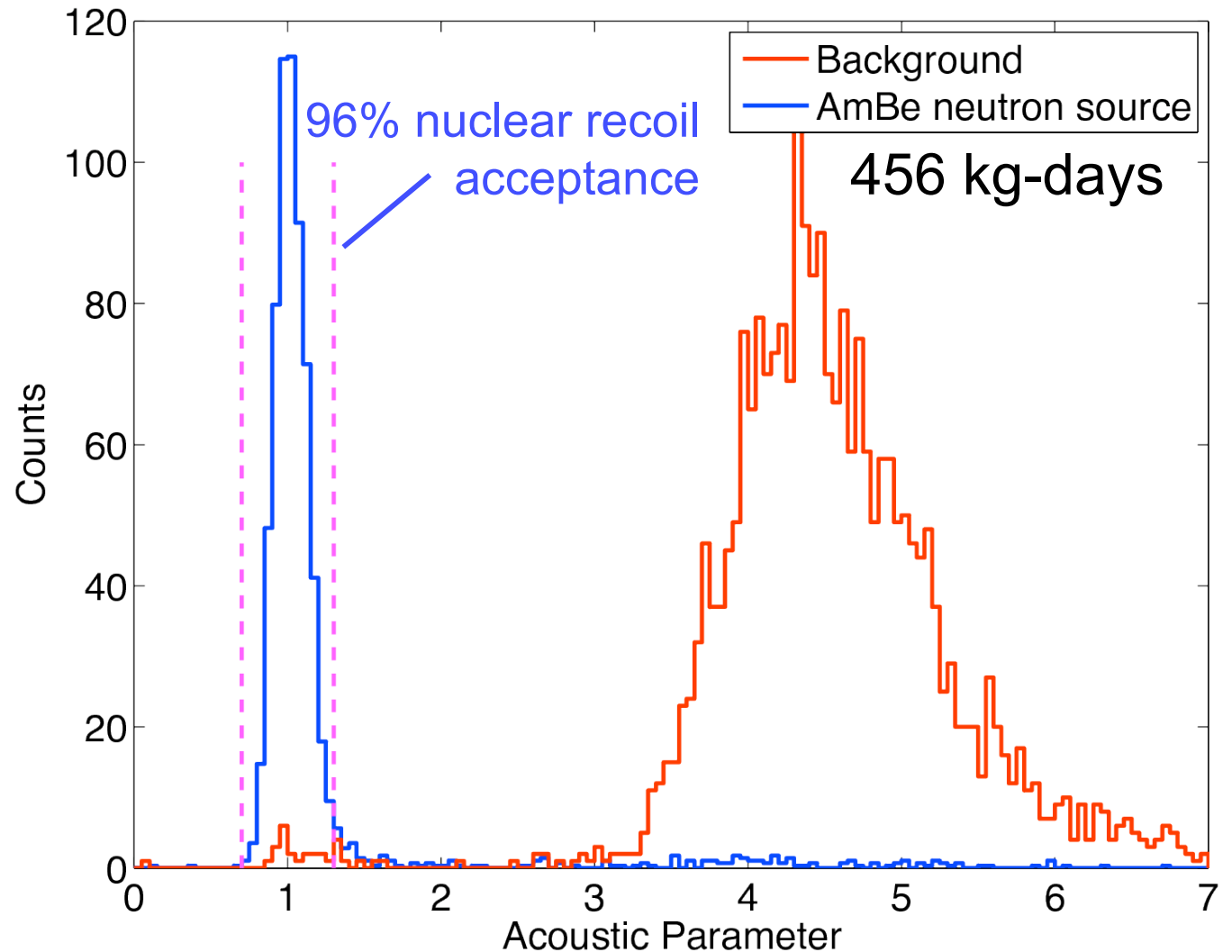


- 17.4, 21.9, 97.3 live-days at 8, 10, 15 keV thresholds
- 4.048 kg target, 79% cut-efficiency for nuclear recoils
 - 90% quality cuts, 92% fiducial cut, 96% acoustic cut

COUPP 4kg @ SNOLAB

“Acoustic Parameter”

- $(\text{Amp} \cdot \omega)^2$
(Normalized and position-corrected)
- Measure of acoustic energy deposited in chamber



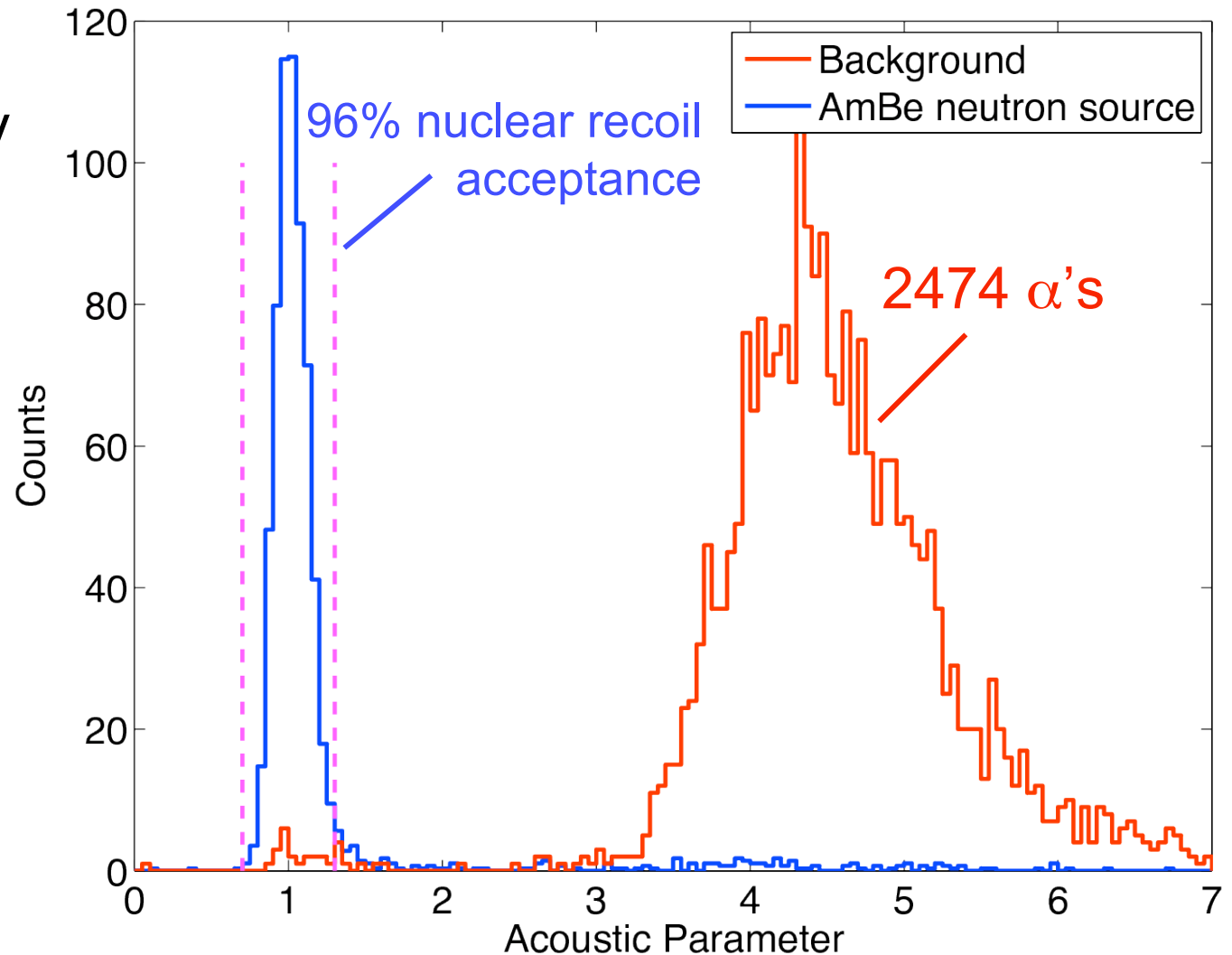
COUPP 4kg @ SNOLAB

- 5.3 alpha-decays / kg-day

- 95% ^{222}Rn , ^{218}Po , ^{214}Po triplets

- >98.9% alpha rejection

- >99.3% alpha rejection in 15 keV data



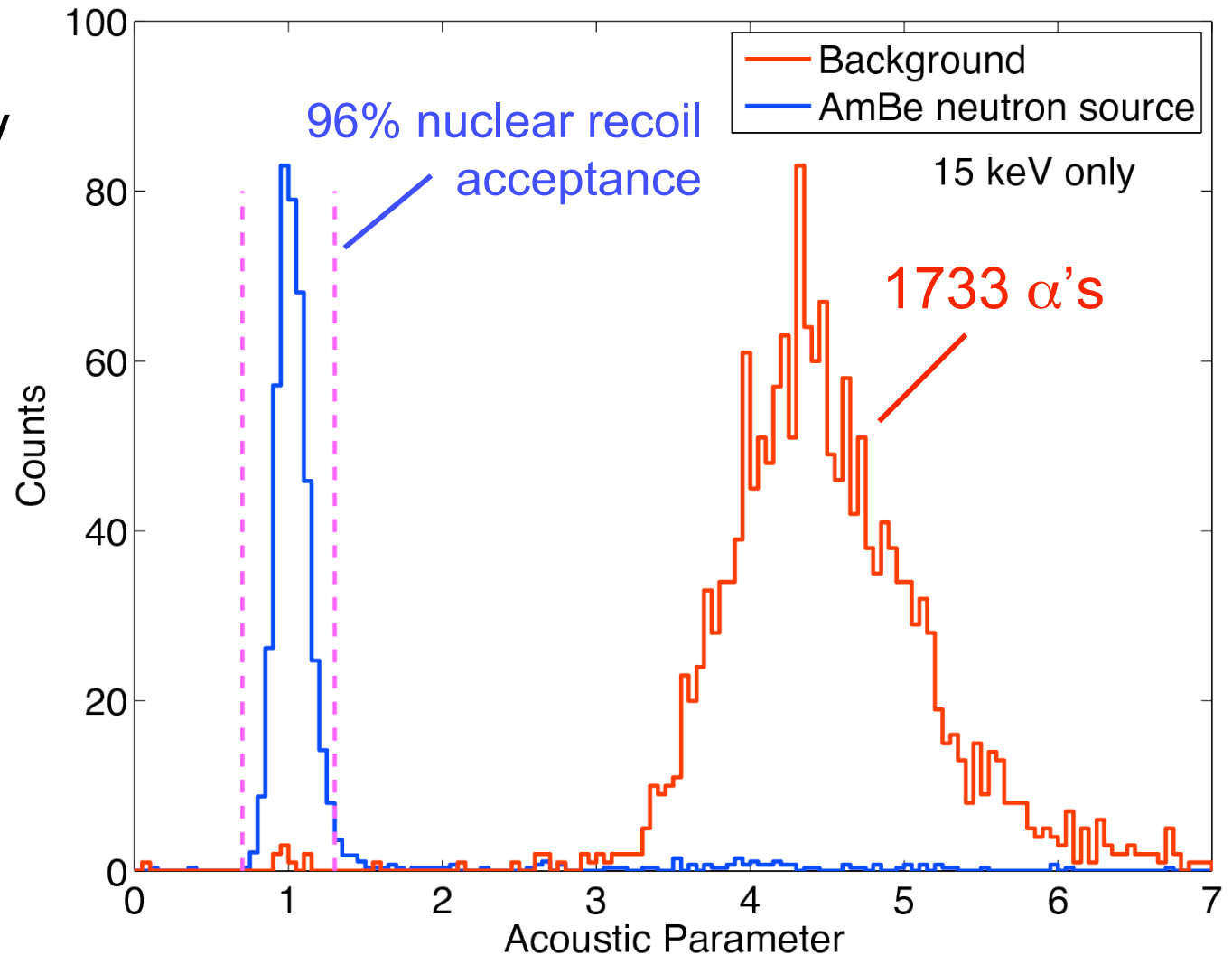
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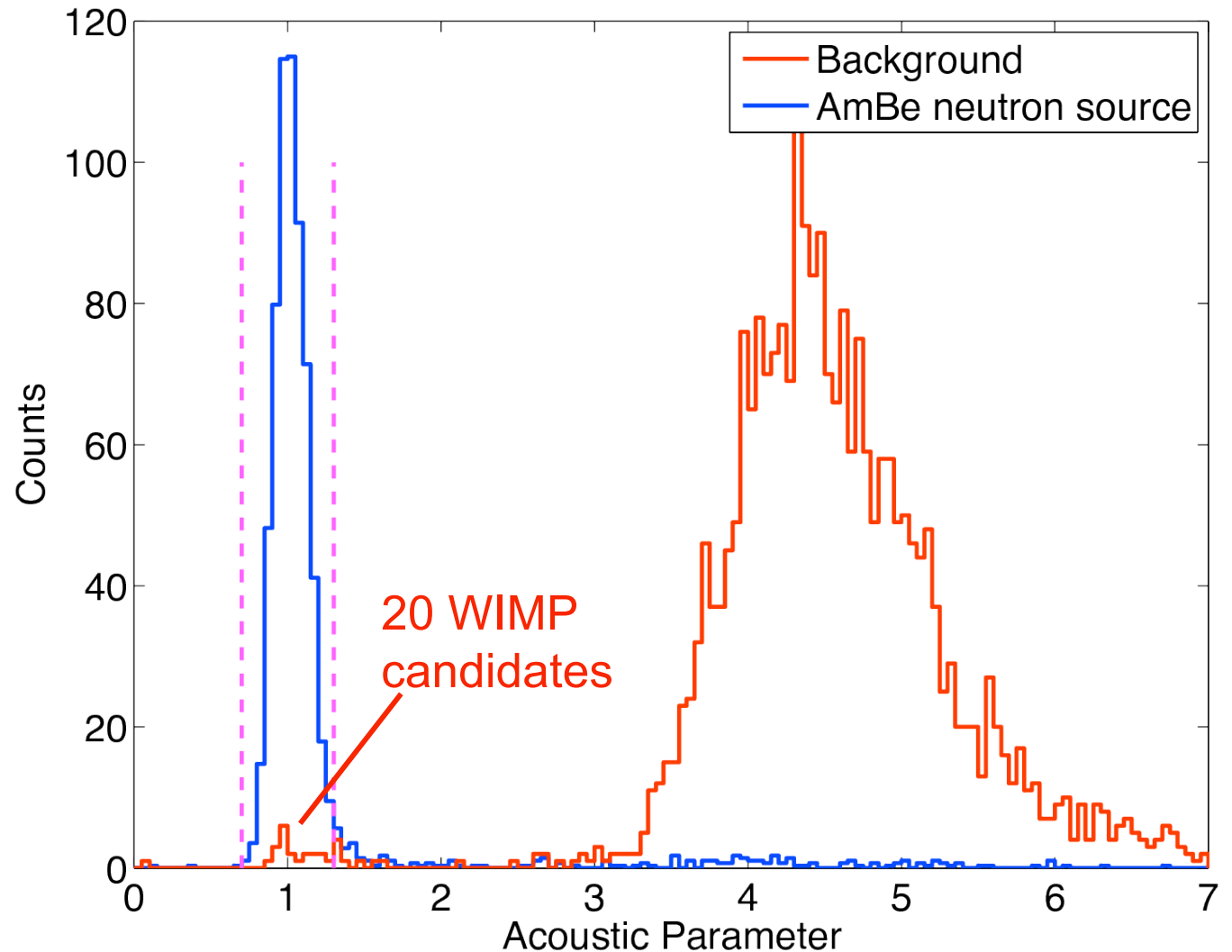
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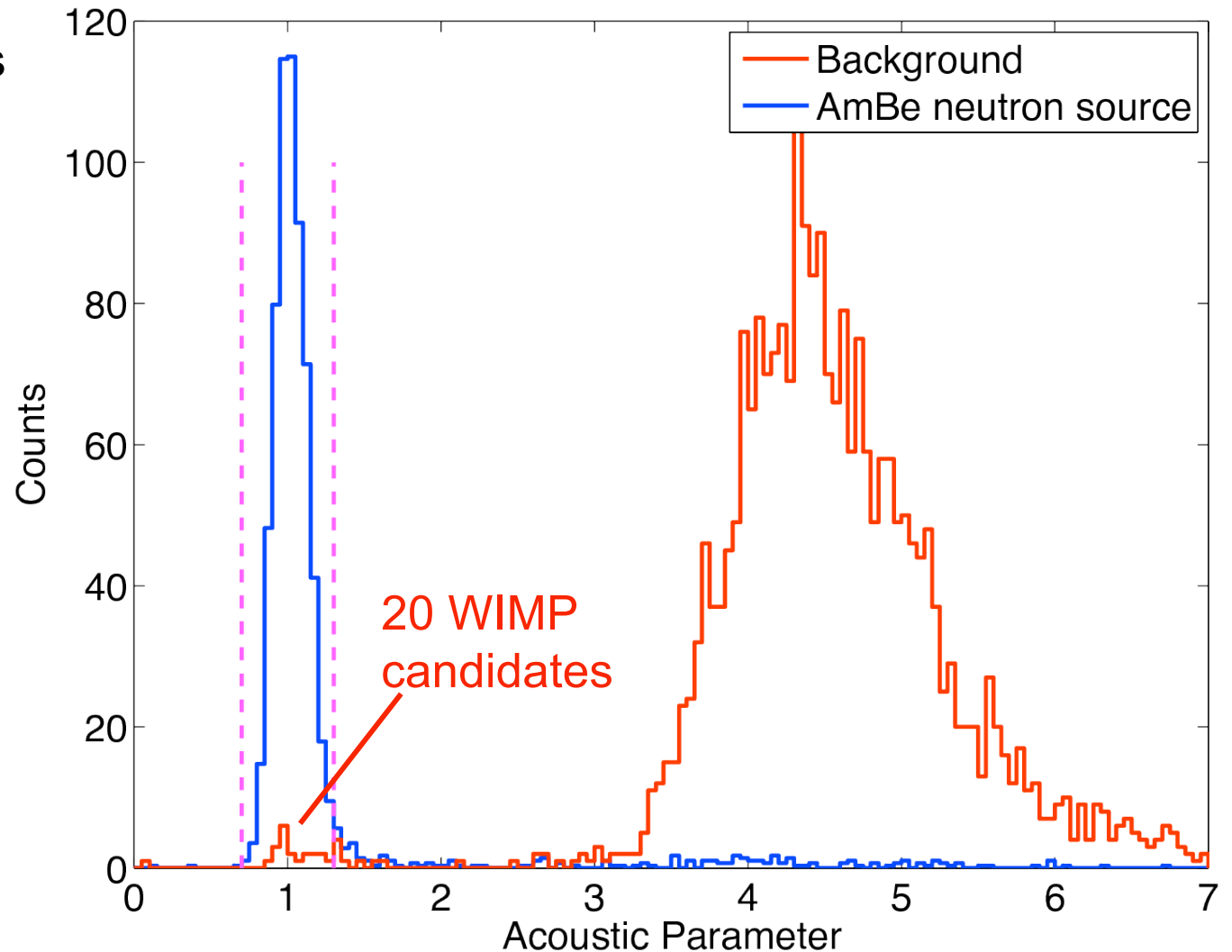
COUPP 4kg @ SNOLAB

- At 8 keV:
 - 6 WIMP candidates
- At 10 keV:
 - 6 WIMP candidates
 - 2 three-bubble events
- At 15 keV:
 - 8 WIMP candidates
 - 1 two-bubble event



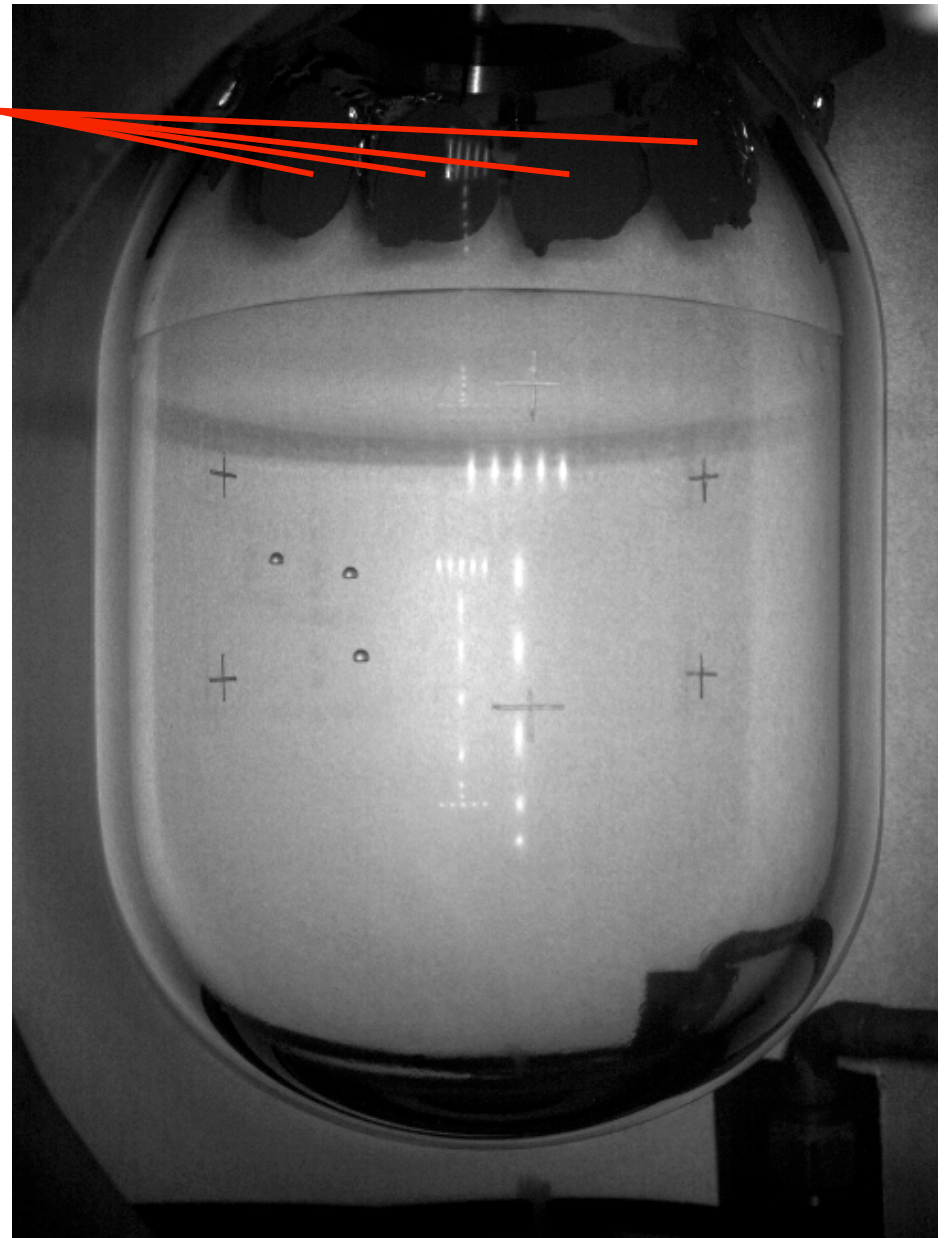
COUPP 4kg @ SNOLAB

- Multi-bubble events mean Neutron Background!
- Calibration gives 3:1 ratio for singles:multiples
 - 3 – 25 singles from neutrons
- $O(0.1)$ per year from cosmic muons, cavern walls

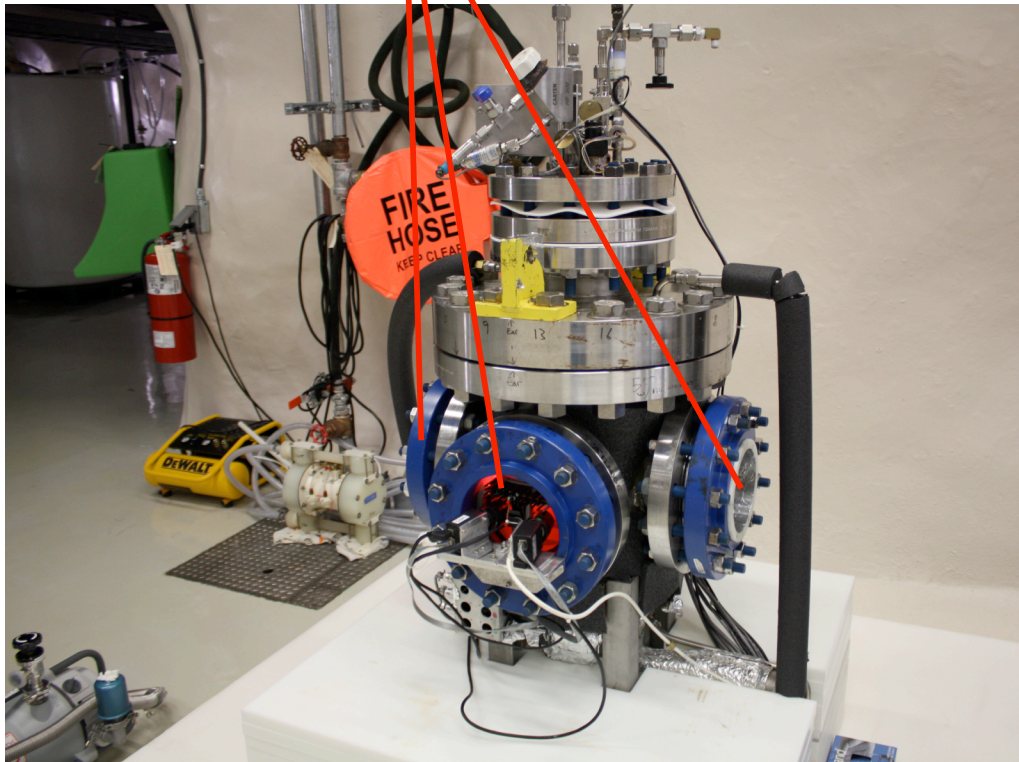


Neutron sources!

- Piezoelectric element is ceramic PZT (Lead zirconate titanate)
- 4.0 ppm ^{238}U
1.9 ppm ^{232}Th
plus lots of modern lead with ^{210}Pb
- Both fission and (α, n) on light elements
- Accounts for ~ 1 background single



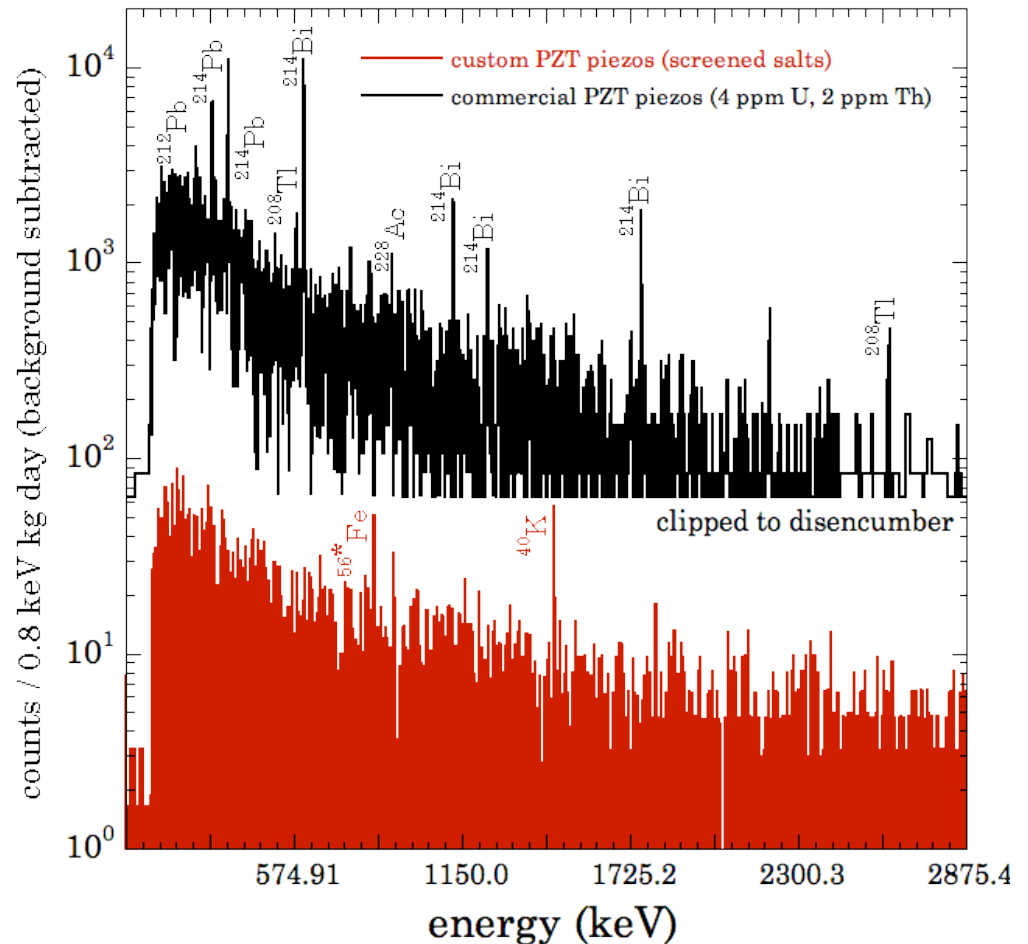
More Neutron sources!



- Camera Viewports
 - Proprietary formulation, probably soda-lime glass
- 0.5 ppm ^{238}U
0.8 ppm ^{232}Th
- Lots of (α, n) on light elements
- Accounts for ~ 4 background singles

Now that we know...

- New piezos made with low-background salts
- New viewport made with synthetic silica
- Next COUPP 4 run begins in January 2012



Now that we know...

■ New Collaborators!

- Custom piezoelectric ceramics:



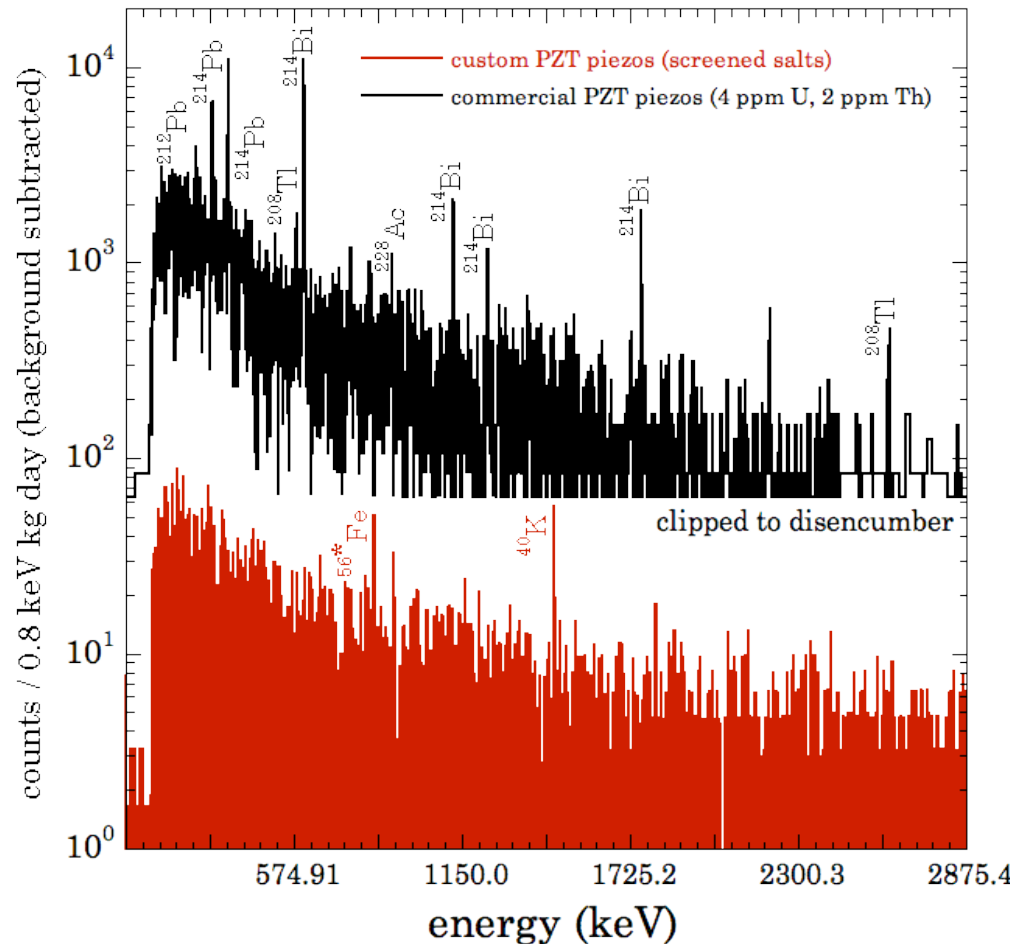
Virginia Tech
Shashank Priya,
Deepam Maurya

- Acoustic modeling:



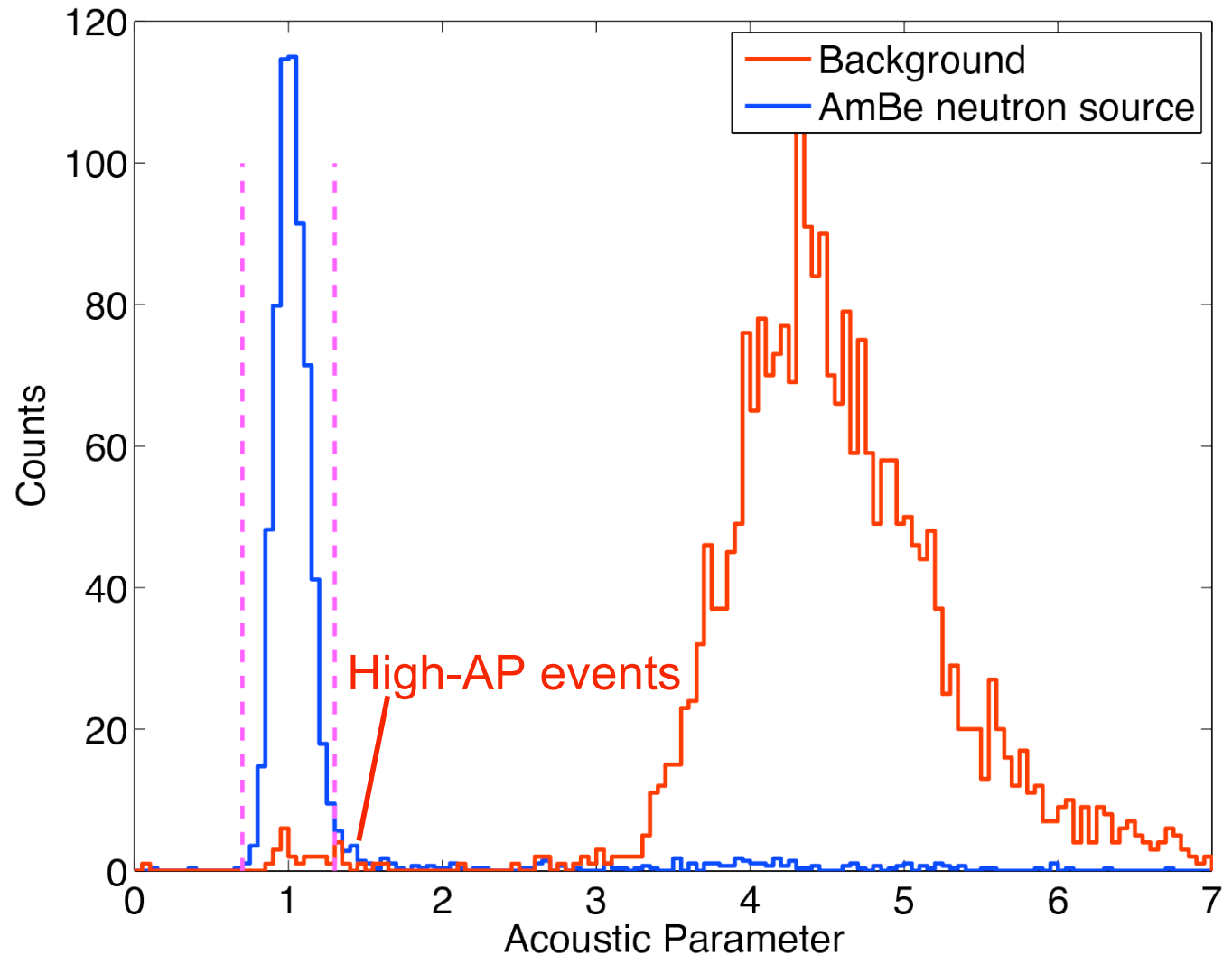
UNIVERSITAT
POLITÈCNICA
DE VALÈNCIA

Universitat Politècnica
de València
Miguel Ramírez, Manu
Cabo



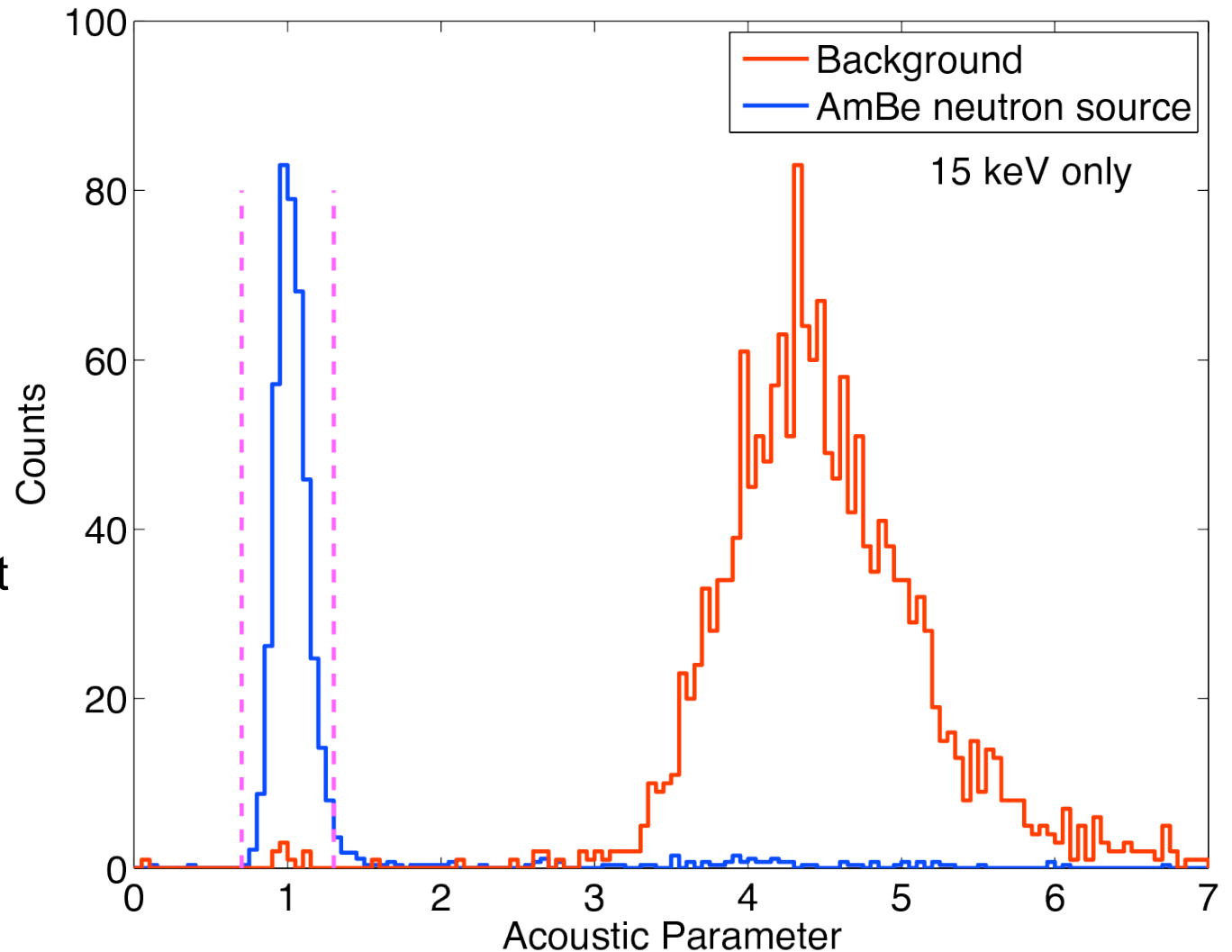
A Second Background?

- High AP
 - 4 evts at 8 keV
 - 2 evts at 10 keV
- Clustered in time at 8 keV
 - 3 High-AP evts in 3 hours
 - 4 evts (1 High-AP) in 9 hours
- <10 minutes after normal events
 - At 8 keV: 4/6 “WIMP”s and all High-AP evts
 - At 10 keV: 3/6 “WIMP”s and 1/2 High-AP evts



A Second Background?

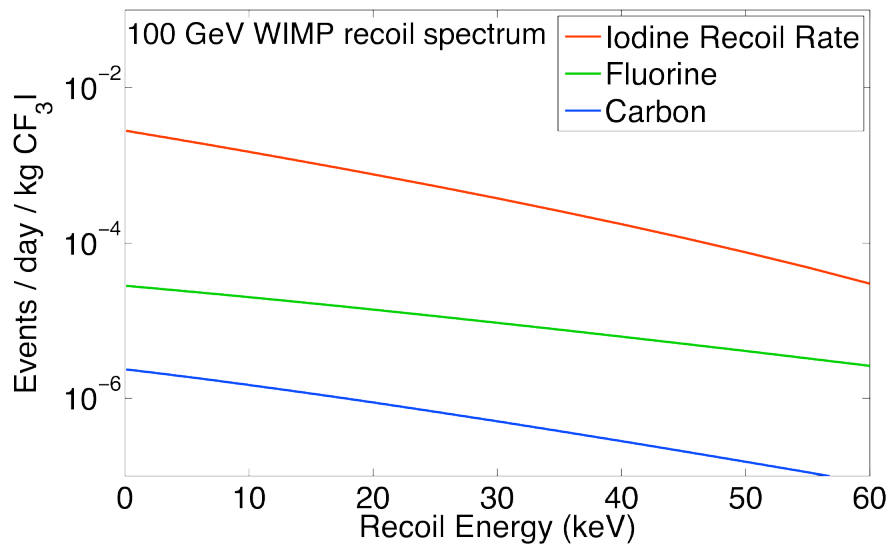
- No anomalous background at 15 keV
- Still investigating source of this background
- Almost certainly not WIMPS!
(But counted as WIMP candidates in limit calculation)



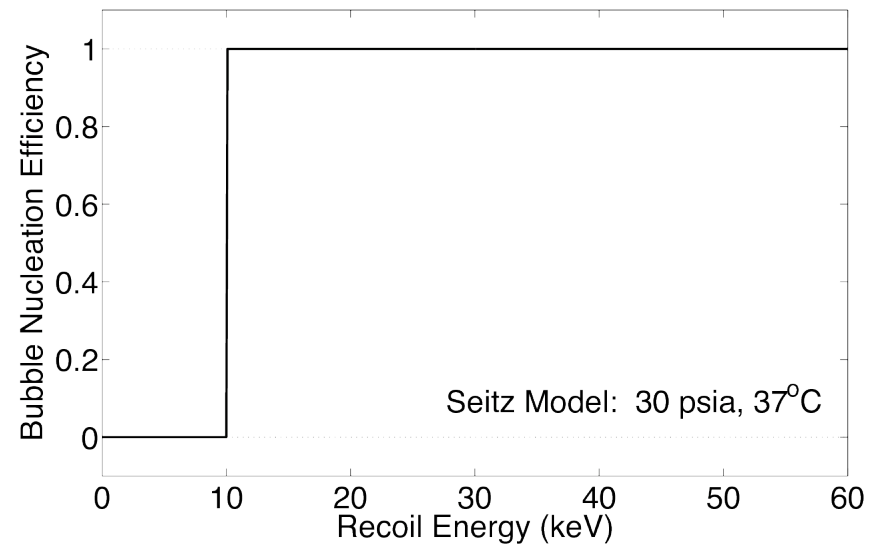
Threshold and Efficiency

WIMP sensitivity =

$$\int \text{WIMP recoil spectrum} \times \text{Bubble Nucleation Efficiency}$$



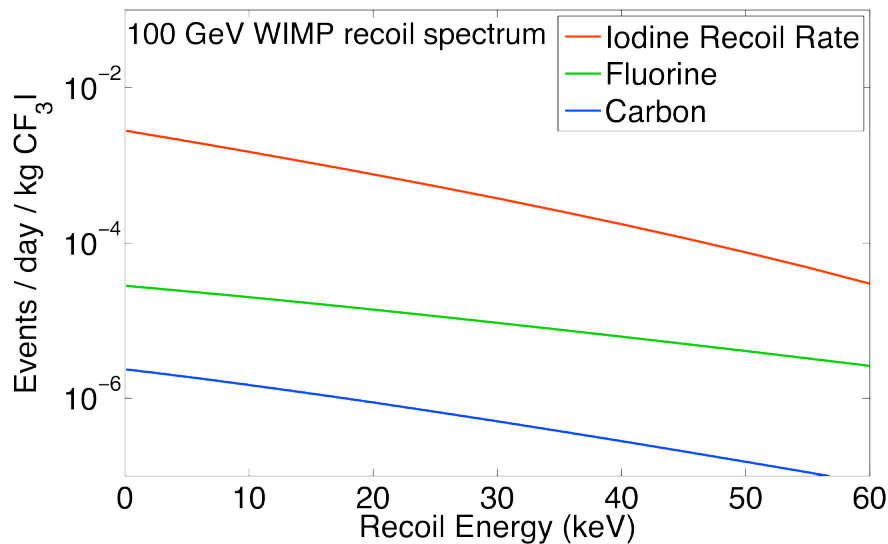
X



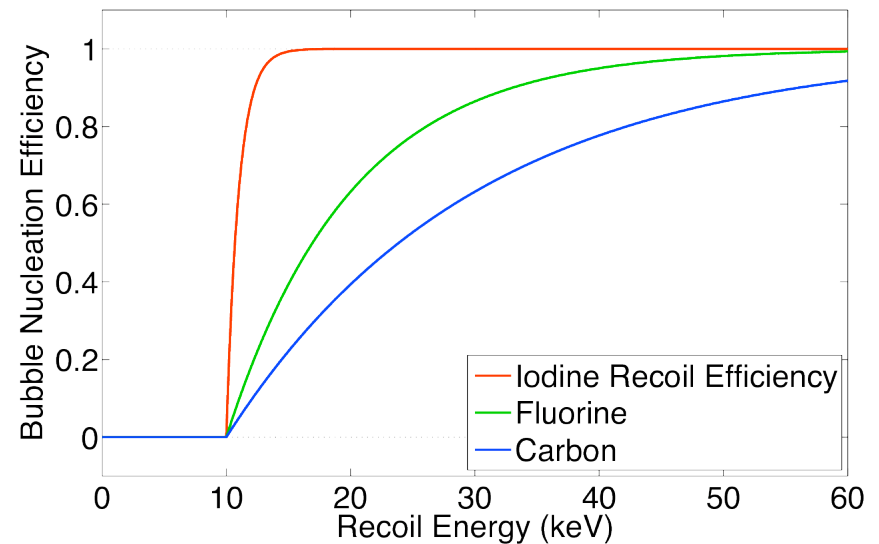
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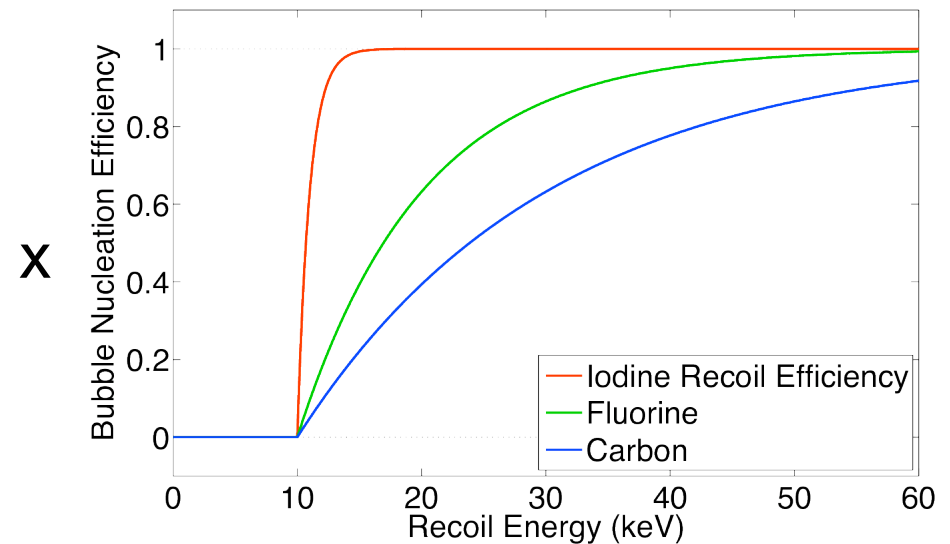
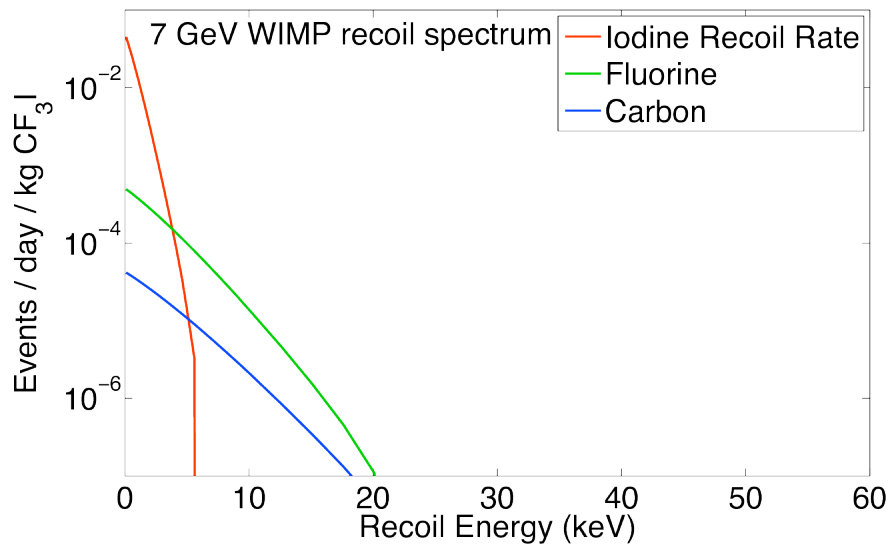
X



Threshold and Efficiency

WIMP sensitivity =

$$\int \text{WIMP recoil spectrum} \times \text{Bubble Nucleation Efficiency}$$



Threshold and Efficiency

- Classical Thermodynamics says-

$$p_v - p_l = \frac{2\sigma}{r_c}$$

$$E_{th} = \underbrace{4\pi r_c^2 \left(\sigma - T \frac{\partial \sigma}{\partial T} \right)}_{\text{Surface energy}} + \underbrace{\left(\frac{4}{3} \pi r_c^3 \rho_v h \right)}_{\text{Latent heat}}$$

- Energy deposition of E_{th} inside length r_c will nucleate bubble (Seitz “Hot-Spike” Model)



Threshold and Efficiency

- Seitz Model Works for:

- 6 keV ^{19}F recoils in C_4F_{10}
[PICASSO Collaboration, arXiv 1011.4553]
- 101 keV ^{218}Po recoils in C_4F_{10}
[PICASSO Collaboration, arXiv 1011.4553]
- 101 keV ^{218}Po recoils in CF_3I

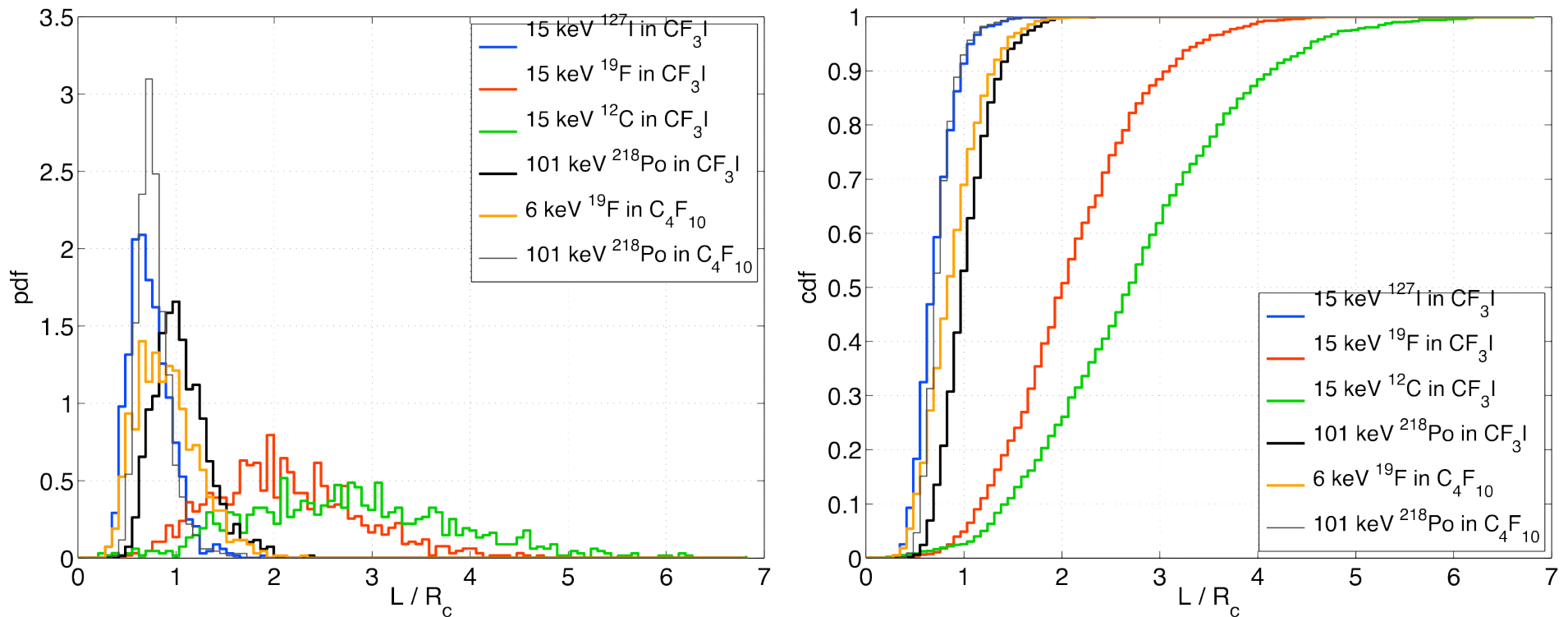


Threshold and Efficiency

- Seitz Model doesn't work for:
 - Generic $O(10)$ keV recoils in CF_3I
 - Neutron calibrations with AmBe and ^{252}Cf source consistently give
 - ~50% the expected rate from MCNP and Geant4 simulations
 - Lower ratio of multiples:singles than simulations

Threshold and Efficiency

■ Which recoils cause problems...



■ 15 keV ^{19}F and ^{12}C in CF_3I have tracks significantly longer than critical radius

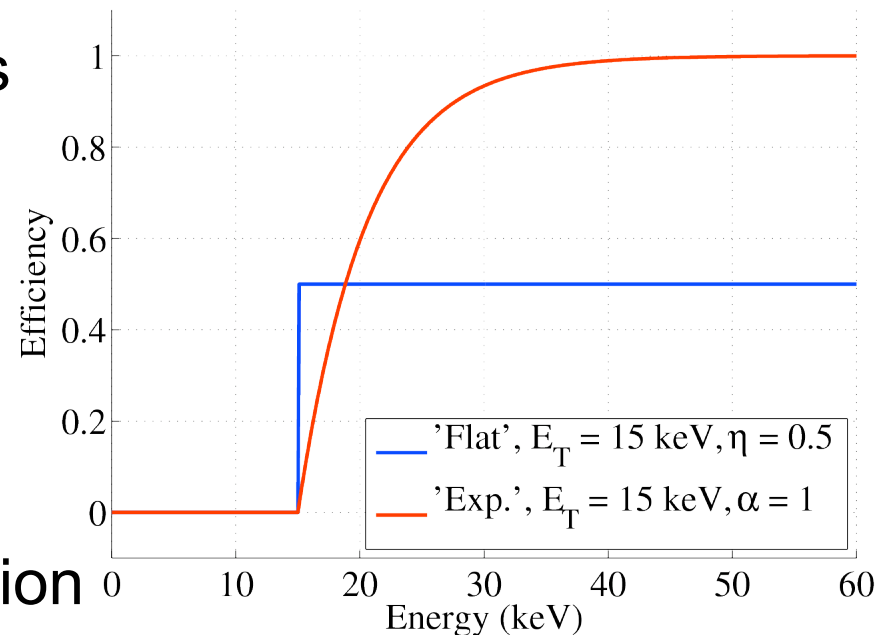
Threshold and Efficiency

■ Current Best Guess

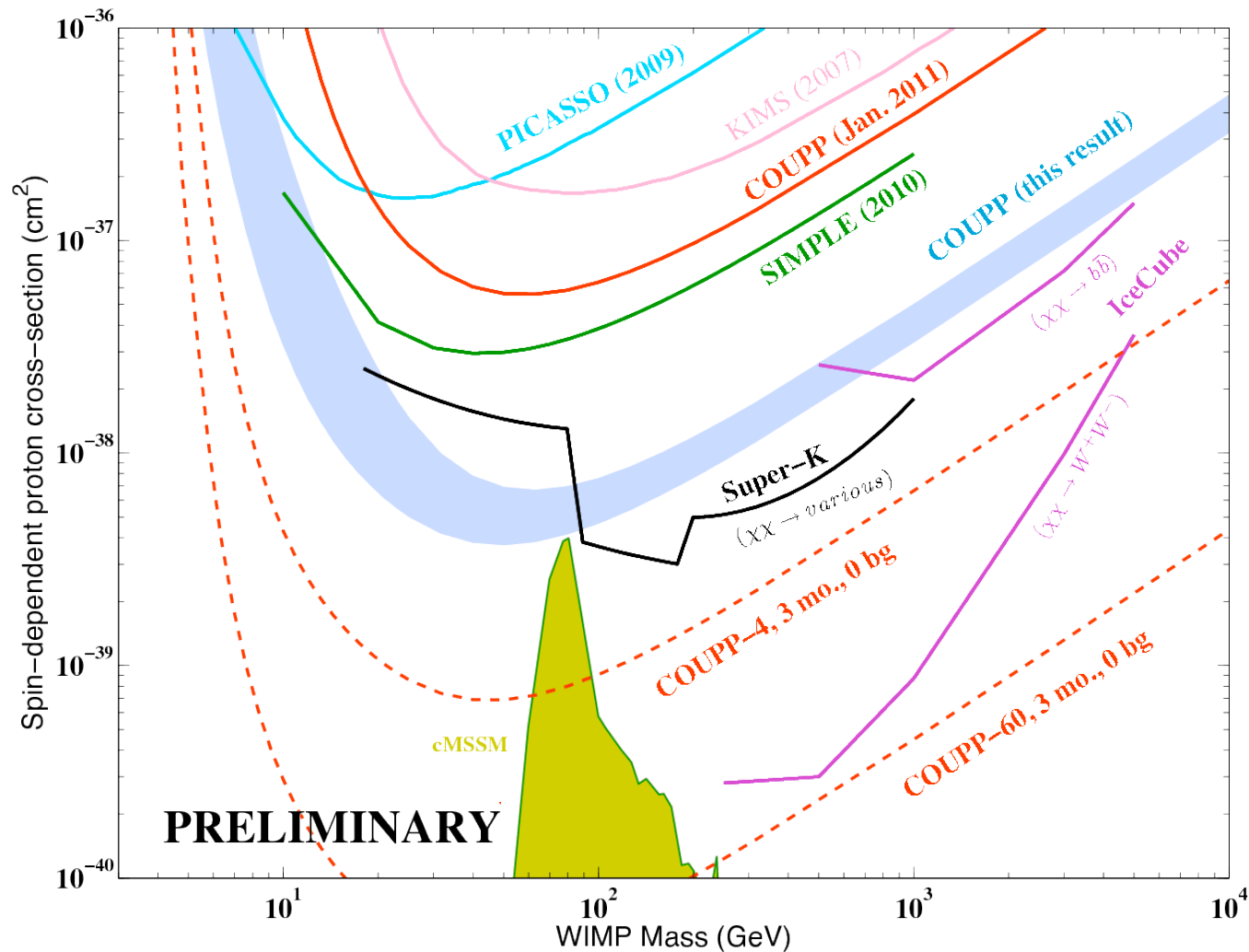
- Seitz model for ^{127}I recoils
- Lower efficiency for ^{19}F and ^{12}C recoils

- Either of these efficiencies for ^{19}F and ^{12}C will reproduce rates and multiplicities observed in calibration

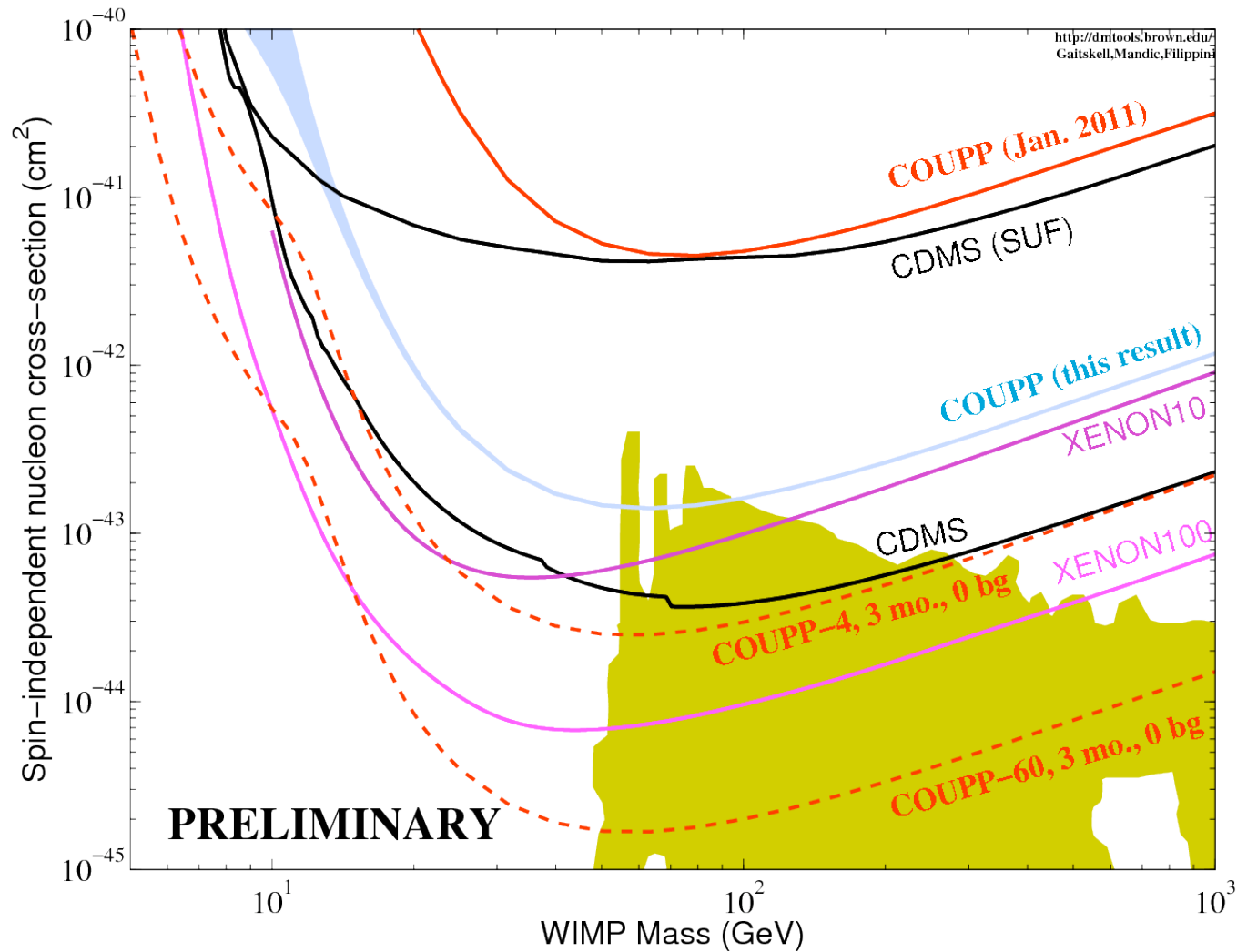
- Need new measurements to answer efficiency question



COUPP 4kg @ SNOLAB



COUPP 4kg @ SNOLAB



- 437 kg-days underground
- >99.3% acoustic alpha rejection
- Clear path to lower neutron backgrounds
- Next 4kg run begins in January
- COUPP60 arrives at SNOLAB later in 2012

COUPP 4kg @ SNOLAB

